# Mass Reduction and Cost Analysis—Light-Duty Pickup Truck Model Years 2020-2025

United States
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# Mass Reduction and Cost Analysis—Light-Duty Pickup Truck Model Years 2020-2025

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Prepared for EPA by
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*This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.*

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## Executive Summary

The United States Environmental Protection Agency (EPA) contracted FEV to conduct an analysis of the potential for reducing the mass of a light-duty pickup truck in the 2020 to 2025 timeframe. The goal of this study was to evaluate the incremental costs of mass reduction levels that are feasible within the given timeframe, without sacrificing utility, performance, or safety. To the extent that cost-effective mass reduction can be achieved, techniques like those described in this report may be employed by manufacturers to reduce greenhouse gas emissions and improve fuel economy.

To support this project, FEV subcontracted with Munro and Associates, Inc.® and EDAG, Inc. Both companies previously assisted FEV on the 2012 Midsize CUV report [1].

A 2011 Chevrolet Silverado Crew Cab 4x4 vehicle[2] was chosen to represent the pickup truck market in North America due to its high annual production volume, and level of technology that is representative of the current market. Selection of the Silverado also enabled incorporation of the modeling of a 2007 Silverado that was completed for a study of advanced plastics and composites technologies by the National Crash Analysis Center (NCAC) at George Washington University, WTH Consulting LLC, and University of Dayton Research Institute for the National Highway Traffic and Safety Administration (NHTSA).[3]

Light duty pickup trucks are designed to meet a broad range of requirements, providing particular utility and performance that are much different from most passenger vehicles. Consumers expect power and ruggedness to satisfy payload and towing requirements, in addition to comfort, ride and handling that approach the performance of passenger cars. These two extremes drive unique design considerations which may both limit the amount of mass reduction achievable in the future, and increase the cost. This analysis includes only those mass reduction ideas which are not expected to degrade the overall function, performance, or safety of the vehicle under any of the customer usage profiles.

Design, material, and manufacturing processes determined likely to be available for the 2020-2025 model year time frame were considered in the mass reduction technology analysis. The critical boundary conditions assumed when assessing the various mass reduction technologies included the following:

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1 Environmental Protection Agency, “Light-Duty Vehicle Mass Reduction and Cost Analysis – Midsize Crossover Utility Vehicle,” EPA-420-R-12-026, August 2012 (http://www.epa.gov/otaq/climate/documents/ 420r12026.pdf)

2 Silverado LT (crew cab) 4x4, 5.3L V8, 6-Speed Automatic Transmission , Vehicle Curb Weight (CW) as purchased 2,454 kg (5,410 lb) , Gross Vehicle Weight (GVW) 3,182 kg (7,000 lb), and Gross Combined Vehicle Weight (GCVW) 6,818 kg (15,000 lb)

3 “Investigation of Opportunities for Light-Weighting Vehicles Using Advanced Plastics and Composites”, National Crash analysis Center, the George Washington University, WTH consulting LLC, University of Dayton Research Institute submitted to NHTSA, DTFH61-09-D-0001, August 6 2012

1. No degradation in function, performance (including payload and towing capacities), or safety from the baseline vehicle.
2. Capable of being mass-produced in the 2020-2025 timeframe (defined as 450,000 units per year).
3. The maximum increase in the direct manufacturing cost of the vehicle should not exceed 10% ($2,430)[4], although individual components may exceed a 10% increase in cost.
4. No change in the type or architecture of the powertrain or any other vehicle system is permitted to gain additional mass-savings. (e.g., turbo charging to enable downsizing of a naturally aspirated internal combustion engine.)

The tools and methodologies utilized in the analysis include those employed in the 2012 Midsize CUVreport. In addition, new methodologies are used to evaluate closures performance as well as to address the unique characteristics and requirements of full-size pickups, including durability, vehicle dynamics, and bed and tailgate performance. The analysis methodology is summarized in the following five steps.

**Step 1: Baseline Vehicle Fingerprinting**

This analysis began with the teardown and benchmarking of a 2011 Silverado vehicle to establish a baseline for analysis. Key attributes were recorded for each component, including mass, size, and material type. As a starting point, the computer-aided engineered (CAE) data for a 2007 Silverado vehicle model developed by the NCAC at the George Washington University was utilized. Differences between the provided 2007 CAE models and the actual 2011 Silverado teardown vehicle hardware were evaluated and selective updates made. The development of the baseline model was supported by comparing a number of criteria to the actual vehicle. Analysis of weight, NVH (noise, vibration, and harshness), Crash and Safety (NHTSA data), Durability, Bumper impact performance, and Vehicle Dynamics were studied. The vehicle components were grouped into 19 vehicle systems.

4 Manufacturing Suggested Retail Price (MSRP) of Vehicle $36,400 US Funds. Estimate OEM vehicle manufacturing cost equals MSRP divided by the Retail Price Equivalent (RPE) ($36,400 MSRP /1.5 RPE = $24,300). Therefore, 10% of OEM vehicle manufacturing cost equals $2,430. ($24,300 * 10%)

**Step 2: Component Level Idea Generation and Binning**

Next, the team conducted a series of idea generation activities to produce mass reduction ideas for the various components in each of the 19 vehicle systems evaluated. Ideas were gathered from a variety of sources including competitive benchmark data, automotive part suppliers, raw material suppliers, published technical papers and journals, and mass reduction subject matter experts both within and outside of the core team. Ideas were graded in a multi-phase selection process considering factors such as function and performance degradation risk, manufacturing feasibility risk, and cost effectiveness in terms of weight savings per change in direct manufacturing cost.

**Step 3: Mass Reduction and Cost Optimization Process**

Individual component mass reduction ideas were assembled in different combinations at the assembly, subsystem, and system levels to create different value propositions. The various combinations of ideas were then placed into an optimization matrix with each unique combination of ideas placed into one of five possible cost groups based on the preliminary estimated cost per kilogram for the forecasted mass reduction. The baseline CAE model underwent a lightweight design optimization processes using the HEEDS MDO (Multi-disciplinary Organization) optimization tool in which the mass of the body-in-white (BIW), closures and bumpers were reduced. This task is done in an iterative process with the CAE process in Step 4.

**Step 4: Selection of Vehicle Mass Reduction Solution**

Upon completion of the matrix, the team reviewed and selected the best mass reduction ideas at the subsystem and system levels, with the goal of achieving the greatest possible vehicle mass reduction at the lowest direct manufacturing cost. The combination of the selected ideas for the trim, powertrain, and chassis components were used together with the primary body and frame results to create a primary vehicle solution. The mathematically predicted results from the HEEDS MDO model were reanalyzed to confirm the design for the primary solution met the targets. Steps 3 and 4 were iterative for the CAE model. The final design concept for the BIW/closures/bumpers is chosen.

**Step 5: Detailed Mass Reduction Feasibility and Cost Analysis**

Once the final solutions for the optimized mass reduced vehicle were selected for all vehicle components, the team began the detailed mass reduction and cost analysis effort. The following items were conducted in this step:

i. Additional work was completed as necessary to ensure the estimated amount of mass reduction was dependable, and achievable without any degradation of function or performance. The depth of this analysis ranged from simply normalizing existing reference vehicle components for differences in size and loading, to detailed analytical calculations.

a. Secondary Mass Savings: After estimating mass reduction levels of trim, chassis, and powertrain components using the above steps, and before considering any secondary mass savings and light-weighting of the body structure (i.e., cabin, closures and box) and frame, the team felt confident a minimum 20% mass reduction could be achieved with secondary mass savings. Based on the 20% minimum prediction, the team revaluated the applicable vehicle systems (e.g., engine, transmission, suspension, brakes, fuel, etc.) for additional mass reduction and cost savings. This approach was somewhat conservative as any additional mass reduction achieved above the 20% value did not take advantage of any further secondary mass-savings.

b. The final mass-reduced trim, chassis, and powertrain system weights (including secondary mass-savings) were updated in the various vehicle level CAE models (**Executive Table 1**) for final iterative runs. Final design updates were made to body structure and frame components to ensure CAE evaluations met the requirements as compared to those achieved by the baseline models. Comprehensive CAE efforts were judiciously employed for the redesign and development of safety critical systems such as the body-in-white (BIW) and frame and mounting, since these systems play a significant role in occupant protection during front, side, and rear collisions.

ii. Detailed cost models were assembled to accurately assess the incremental direct manufacturing cost impact of the proposed mass reduction measures. The models are activity-based cost models, and represent the actual manufacturing operations and processes used to produce the components. Key manufacturing cost factors (e.g., material, labor, manufacturing overhead, mark-up, tooling) are tracked at the component, subsystem and system levels.

**Executive Table 1: CAE Models and Load Cases used to Validate Mass Reduction Concepts**

| System | | Load case | Measure | No. |
|---|---|---|---|---|
| NVH | Frame | Static Bending | Global Bending Stiffness | 1 |
| | | Static Torsion | Global Torsion Stiffness | 2 |
| | Cabin | Static Bending | Global Bending Stiffness | 3 |
| | | Static Torsion | Global Torsion Stiffness | 4 |
| | Cargo Box | Static Bending | Global Bending Stiffness | 5 |
| | | Static Torsion | Global Torsion Stiffness | 6 |
| | Body On Frame | Static Bending | Global Bending Stiffness | 7 |
| | | Static Torsion | Global Torsion Stiffness | 8 |
| Crash/Safety | Full Vehicle | FMVSS 208 - 35 MPH Flat Frontal Crash (UN NCAP) | Pulse<br>Crush<br>Time-To-Zero Velocity<br>Dash Intrusion | 9 |
| | | IIHS - 40 mph ODB Frontal Crash | Pulse<br>Crush<br>Time-To-Zero Velocity<br>Dash Intrusion | 10 |
| | | FMVSS 214 - 38.5 MPH MDB Side Impact (US SINCAP) | B-Pillar Velocity<br>Side Structures Intrusion | 11 |
| | | IIHS - 31 MPH MDB Side Impact | B-Pillar Velocity<br>B-Pillar Intrusions<br>Survival Space<br>Exterior Crush | 12 |
| | | FMVSS 214 - 20 MPH, 5$^{th}$ Percentile Pole Side Impact | B-Pillar Velocity<br>B-Pillar Intrusions<br>Structures Intrusions | 13 |
| | | FMVSS 301 - 50 MPH MDB Rear Impact | Under Structural Zone Deformation<br>Door Operability<br>Fuel Tank Damage | 14 |
| | | FMVSS 261a - Roof Crush | Roof Strength to Weight Ratio | 15 |
| | | FMVSS 581 - Bumper Impact | Front End Deformation | 16 |
| Durability | Frame | Fatigue | Component Life Cycle | 17 |
| | Doors | Frame Rigidity | Stiffness | 18 |
| | | Beltline Compression | Stiffness | 19 |
| | | Beltline Expansion | Stiffness | 20 |
| | | Torsion | Twist Stiffness | 21 |
| | | Sag | Vertical Deformation | 22 |
| | | Oil Canning | Outer Panel Deformation | 23 |
| | Hood | Bending | Stiffness | 24 |
| | | Torsion | Twist Stiffness | 25 |
| | | Oil Canning | Outer Panel Deformation | 26 |
| | Tailgate | Torsion | Twist Stiffness | 27 |
| | | Oil Canning | Outer Panel Deformation | 28 |
| Vehicle Dynamics | Full Vehicle | Static Bending | Understeer Gradient<br>Cornering Compliance<br>Roll Gradient | 29 |
| | | Static Torsion | Tire Load | 30 |
| | | Static Bending | Steering Response Phase Lag<br>Steering Response Gain | 31 |
| | | Static Torsion | Track Width/(2 x CG Height) | 32 |

A summary of the results for mass reduced and cost impact are shown in **Executive Table 2**Error! Reference source not found.. For each vehicle system evaluated, the starting mass, final mass, percent system mass reduction, and percent vehicle mass reduction are provided along with the Net Incremental Direct Manufacturing Cost (NIDMC) and tooling impact. The net mass reduction achieved was 560.9 kg (or 22.9% vehicle mass reduction) at a cost increase of $2,074 per vehicle, or an average cost of $3.70 per kg. The costs shown are net incremental direct manufacturing costs not inclusive of certain OEM markups. In addition these costs are considered mature, high volume, mass-production costs.

Tooling impact was calculated to be a decrease of $0.01 per kg at the mass reduction point of 22.9% for a total of $3.69 per kg increase. The tooling impact is the estimated difference in tooling costs between the baseline (i.e., production stock version of the 1500 Series Silverado) and mass reduced version. A simple means for defining tooling is everything which directly touches the part during manufacturing (i.e., dies, molds, welding tips, cutting tools, fixtures, gauges, etc.) Tooling does not include manufacturing capital equipment such as injection mold machines, die casting machines, stamping presses, conveyor lines and welding equipment.

This study does not include a comprehensive, full vehicle, NVH evaluation. Therefore the overall percentage weight loss is reduced in order to account for the aspects of mass reduction which would require additional countermeasures for NVH. This could include additional hood insulation, body-in-white mastic, weight counterbalances, etc. As a result, an NVH countermeasure allowance of 50 kg is removed from the mass savings at a cost estimate of $3.00 kg. So overall, the mass reduced is 20.8% at $4.35 per kg (also $4.35 per kg with tooling).

**Executive Table 3** provides a summary of the additional mass reduction associated with secondary mass savings (SMS) for the applicable vehicle systems. The body structure and frame and mounting system analyses were only evaluated with consideration to secondary mass savings**Error! Reference source not found.**. For the eight systems valuated with and without secondary mass savings, an additional 83.9 kg were saved (or 3.4% of the baseline vehicle mass). The cost savings associated with the secondary mass savings equaled $68.74, translating to an average $0.82 per kg ($68.74/83.9 kg).

**Executive Table 2: Mass Reduction and Net Incremental Direct Manufacturing Cost (NIDMC) Impact for Each Vehicle System Evaluated**

| Item | System ID | Description | Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC "$" (2) | Cost/ Kilogram NIDMC "$/kg" (2) | Cost/ Kilogram NIDMC + Tooling "$/kg" (2) | System Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | **Mass Reduction Impact by Vehicle System (Includes Secondary Mass Savings)** | | | | | | |
| | | **1500 Series Chevrolet Silverado Pick-Up Truck** | | | | | | | |
| 1 | 01 | Engine System | 239.9 | 31.8 | -92.83 | -2.92 | -2.63 | 13.3% | 1.3% |
| 2 | 02 | Transmission System | 145.3 | 39.4 | -96.57 | -2.45 | -2.47 | 27.1% | 1.6% |
| 3 | 03A | Body System Group -A- ( Body Sheetmetal) | 574.7 | 207.1 | -1194.86 | -5.77 | -5.77 | 36.0% | 8.4% |
| 4 | 03B | Body System Group -B- (Body Interior) | 247.0 | 34.0 | -127.23 | -3.74 | -3.78 | 13.8% | 1.4% |
| 5 | 03C | Body System Group -C- (Body Exterior Trim) | 40.5 | 2.1 | 2.73 | 1.28 | 1.28 | 5.3% | 0.1% |
| 6 | 03D | Body System Group -D- (Glazing & Body Mechatronics) | 50.9 | 4.5 | 2.30 | 0.51 | 0.51 | 8.9% | 0.2% |
| 7 | 04 | Suspension System | 301.2 | 105.4 | -154.90 | -1.47 | -1.48 | 35.0% | 4.3% |
| 8 | 05 | Driveline System | 183.8 | 20.4 | 38.01 | 1.86 | 1.89 | 11.1% | 0.8% |
| 9 | 06 | Brake System | 101.0 | 45.8 | -148.92 | -3.25 | -3.35 | 45.4% | 1.9% |
| 10 | 07 | Frame and Mounting System | 267.6 | 23.7 | -54.42 | -2.30 | -2.30 | 8.9% | 1.0% |
| 11 | 09 | Exhaust System | 38.4 | 6.9 | -13.69 | -1.97 | -1.97 | 18.1% | 0.3% |
| 12 | 10 | Fuel System | 26.3 | 7.3 | 11.92 | 1.62 | 1.77 | 27.9% | 0.3% |
| 13 | 11 | Steering System | 32.5 | 8.5 | -147.46 | -17.44 | -17.45 | 26.0% | 0.3% |
| 14 | 12 | Climate Control System | 20.3 | 1.9 | 14.71 | 7.59 | 7.59 | 9.5% | 0.1% |
| 15 | 13 | Information, Gage and Warning Device System | 1.6 | 0.2 | 0.66 | 2.66 | 2.97 | 15.7% | 0.0% |
| 16 | 14 | Electrical Power Supply System | 21.1 | 12.8 | -172.73 | -13.49 | -13.44 | 60.6% | 0.5% |
| 17 | 15 | In-Vehicle Entertainment System | 2.2 | 0.0 | 0.00 | 0.00 | 0.00 | 0.0% | 0.0% |
| 18 | 17 | Lighting System | 9.6 | 0.4 | -2.00 | -5.18 | -5.18 | 4.0% | 0.0% |
| 19 | 18 | Electrical Distribution and Electronic Control System | 33.6 | 8.5 | 61.44 | 7.26 | 7.27 | 25.2% | 0.3% |
| 20 | 00 | Fluids and Miscellaneous Coating Materials | 116.8 | 0.0 | 0.00 | 0.00 | 0.00 | 0.0% | 0.0% |
| | | a. Analysis Totals Without NVH Counter Measures → | **2454.4** | **560.9** | **-2073.82** | **-3.70** | **-3.69** | **n/a** | **22.9%** |
| | | b. Vehicle NVH Counter Measures (Mass & Cost ) → | 0.0 | -50.0 | -150.00 | **n/a** | **n/a** | **n/a** | **n/a** |
| | | c. Analysis Totals With NVH Counter Measures → | **2454.4** | **510.9** (Decrease) | **-2223.82** (Increase) | **-4.35** (Increase) | **-4.35** (Increase) | **n/a** | **20.8%** |

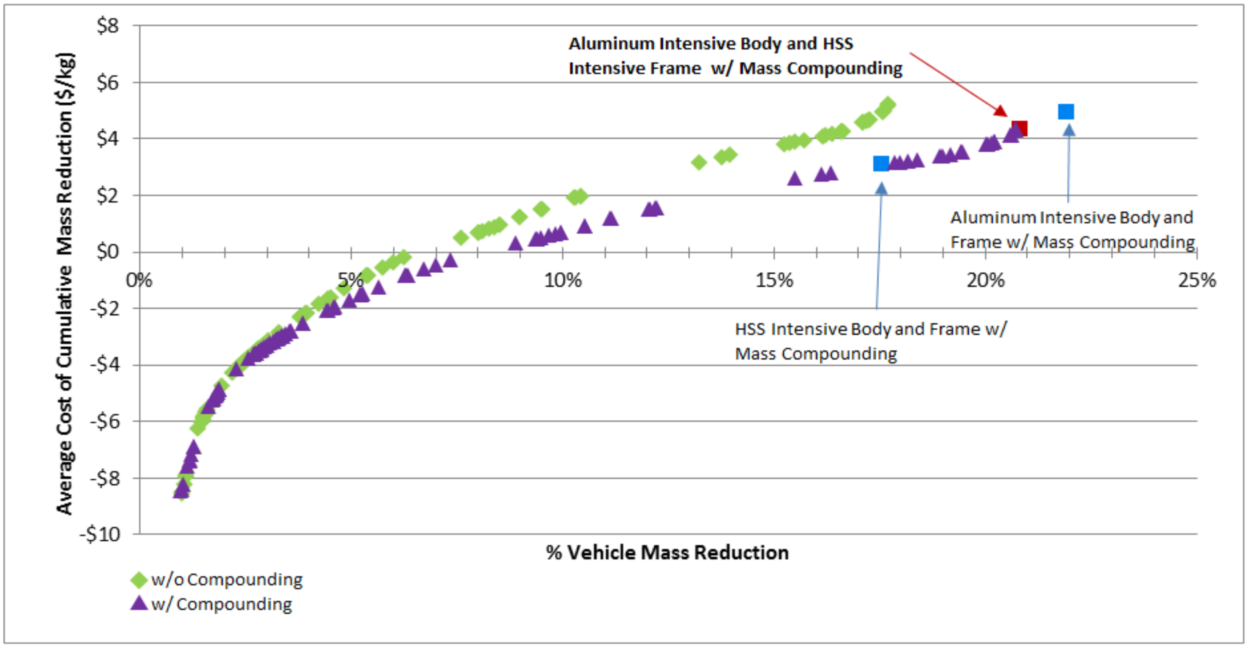
(1) Negative value (i.e., **-X.XX** ) represents an increase in mass
(2) Negative value (i.e., **-$X.XX**) represents an increase in cost

**Executive Table 3: Secondary Mass-Savings Impact for Applicable Vehicle Systems**

| | | | Secondary Mass Savings (SMS) Impact by Vehicle System | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | System ID | Description | Base Mass "kg" | Mass Reduction with SMS "kg" (1) | Mass Reduction without SMS "kg" (1) | Incremental Mass Reduction from SMS "kg" (1) | Cost Impact NIDMC with SMS "$" (2) | Cost Impact NIDMC without SMS "$" (2) | Savings from SMS "$" (2) | Cost/ Kilogram NIDMC with SMS "$/kg" (2) | Cost/ Kilogram NIDMC without SMS "$/kg" (2) | Cost Savings/ Kilogram NIDMC from SMS "$/kg" (2) |
| | | | | | | | | | | | | |
| 1500 Series Chevrolet Silverado Pick-Up Truck | | | | | | | | | | | | |
| 1 | 01 | Engine System | 239.9 | 31.8 | 23.8 | 8.0 | -92.83 | -114.63 | 21.81 | -2.92 | -4.82 | 1.90 |
| 2 | 02 | Transmission System | 145.3 | 39.4 | 34.2 | 5.2 | -96.57 | -128.20 | 31.64 | -2.45 | -3.75 | 1.30 |
| 3 | 03A | Body System Group - A- ( Body Sheetmetal) | 574.7 | 207.1 | 190.7 | 16.4 | -1194.86 | -1125.15 | -69.71 | -5.77 | -5.90 | 0.13 |
| 7 | 04 | Suspension System | 301.2 | 105.4 | 83.1 | 22.4 | -154.90 | -260.84 | 105.94 | -1.47 | -3.14 | 1.67 |
| 9 | 06 | Brake System | 101.0 | 45.8 | 43.9 | 2.0 | -148.92 | -167.87 | 18.95 | -3.25 | -3.83 | 0.58 |
| 10 | 07 | Frame and Mounting System | 267.6 | 23.7 | 0.0 | 23.7 | -54.42 | 0.00 | -54.42 | -2.30 | 0.00 | -2.30 |
| 11 | 09 | Exhaust System | 38.4 | 6.9 | 6.3 | 0.6 | -13.69 | -19.54 | 5.85 | -1.97 | -3.08 | 1.11 |
| 12 | 10 | Fuel System | 26.3 | 7.3 | 1.6 | 5.7 | 11.92 | 3.25 | 8.67 | 1.62 | 2.02 | -0.40 |
| | | a. Analysis Totals Without NVH Counter Measures → | **1694.5** | **467.5** | **383.6** | **83.9** | **-1744.26** (Increase) | **-1813.00** (Increase) | **68.74** | **-3.73** (Increase) | **-4.73** (Increase) | **0.82** |

(1) Negative value (i.e., **-X.XX** ) represents an increase in mass
(2) Negative value (i.e., **-$X.XX**) represents an increase in cost

In addition to developing the net incremental direct manufacturing cost (NIDMC) for a single mass-reduced light-duty pickup truck solution, FEV also developed two cost curves (cost per kg versus percent vehicle mass reduction) to estimate the cost impact at alternative percent vehicle mass reduction points (**Executive Figure 1**). Starting at the greatest mass reduction value, the components' mass-saving and cost impact were progressively summed to establish a non-compounded cost curve (i.e., a curve without secondary mass savings). By linearly interpolating the level of compounding, established from the primary vehicle solution (i.e., Aluminum Intensive Body and HSS Intensive Frame), and adding the benefit to the non-compounded vehicle mass reductions, a cost curve with compounding was also developed.




**Executive Figure 1: Light-Duty Pickup Truck Cost Curves With and Without Mass Compounding**

Formulas for a Piecewise and 5$^{th}$ Order Polynomial cost curve, generated from the compounded cost curve above, are found in **Executive Table 4** below. The formulas include the NVH countermeasure allowance. Additional details on cost curve development can be found in **Section 2.1.2** of the report.

**Executive Table 4: Formulas for Calculating Vehicle Cost/Kilogram for Vehicle Mass reduction Less Than 21.9%**

| Trendline Description | Cost/Kilogram Mass-Reduction Formula | % Vehicle Mass Reduction Zone |
|---|---|---|
| Piecewise w/ Mass Compounding/Secondary Mass Savings | $/kg = 219.73*(VMR) - 9.8 | 0% < VMR ≤ 3.52% |
| | $/kg = 36.682*(VMR) - 3.3575 | 3.52% < VMR ≤ 21.9% |
| 5th Order Polynomial w/ Mass Compounding/Secondary Mass Savings | $/kg = 713208*(VMR)^5 - 417980*(VMR)^4 + 91693*(VMR)^3 - 9415.4*(VMR)^2 + 496.04*(VMR) - 11.866 | 0% < VMR ≤ 20.8% |

The following report provides an in-depth review of the methodology, assumptions, verification methods, and detailed results attained in the light-duty pickup truck mass reduction and cost analysis. Supplemental information is also available on EPA's website (www.epa.gov/otaq/) including cost models used to develop the Net Incremental Direct Manufacturing Costs, the CAE files used in the evaluation of the vehicle crash, NVH, dynamics, and durability models.

# 1. Introduction and Program Objectives

## 1.1 Analysis Background

In August 2012, the U.S. Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) issued the final rule making to reduce greenhouse gas (GHG) emissions and improve the fuel economy of model years 2017 and beyond[5] light-duty vehicles. These regulations build upon the first phase of standards for model years 2012 through 2016, so that in 2025 the average industry fleet-wide level of emissions is projected to be 163 grams per mile of carbon dioxide, which is equivalent to a CAFE value of 54.5[6] miles per gallon, if achieved exclusively through fuel economy improvements. In response to these regulations, manufacturers have begun to implement a wide range of advanced vehicle, powertrain and driveline technologies such as turbocharging with engine downsizing, direct injection, variable valve timing and lift, advanced transmissions, automated start-stop systems, electric-hybridization, and aerodynamic improvements.

Another promising technology for reducing vehicle GHG emissions, and the focus of this work, is reduction of vehicle weight. Mass reduction is a fundamental strategy for reducing emissions because lighter vehicles require less energy to accelerate. Mass reduction can be accomplished without compromising vehicle performance, interior volume and utility by combining lightweight materials and innovative vehicle designs. There are many examples of mass reduced designs currently in production today that use lightweight materials such as high strength steels, aluminums, magnesium, composites, engineering plastics and other materials (ATS, CTS, F150, Mustang, BMWi3, Audi A8, Range Rover SUV, etc.). Mass reduction can also be cost effective, for as the vehicle becomes lighter, the load requirements on many components are reduced, creating a virtuous cycle whereby additional, or "secondary" mass reduction can be achieved by redesigning those components. Appropriate light-weight vehicle designs can even result in improvements in vehicle performance attributes where greater mass is detrimental, such as handling and durability. Realizing the full potential of these benefits requires a systems approach to design, due to the many inter-relationships between the various parts on a vehicle. In particular, because the vehicle structure itself is often a good candidate for mass reduction, the effects on crash safety and overall structural noise, vibration, and

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5 EPA's regulation contains standards for 2017-2025. NHTSA is required by Congress to set CAFE standards only five years at a time, but presents the non-final "augural" standards for 2022-2025 in their rulemaking in the interest of aiding manufacturers in future product planning and of harmonization with EPA's greenhouse gas emission standards. Final CAFE standards for MYs 2022-2025 will be established by NHTSA in a future rulemaking, based on the information available to the agency at that future time.

6 Label values are calculated by using the CAFE values in a derived 5 cycle calculation and weighting the resultant city/highway values.

harshness (NVH) must be evaluated to make sure that performance for the new design is maintained.

A number of previous studies have demonstrated that by using a systems approach mass reduction can be accomplished without compromising vehicle performance, interior volume, or utility by combining lightweight materials and innovative vehicle design. A listing of these most recent studies can be found in **Table 1.2-1**. As is the case with other advanced technologies for reducing GHG emissions, mass reduction implementation may depend on the particular vehicle segment (e.g., Small Car, Mid-Size Car, Full-Size Car, Mid-Size Pickup, Full-Size Pickup), and some technologies may not be as beneficial, or be entirely feasible for a given vehicle segment due to existing functional or performance limitations. For example, the use of aluminum in the body structure may be achievable for vehicles with unibody structures and the body of body on frame vehicles, however has not yet proven feasible for the pickup truck ladder frame which is designed to tow heavy loads (e.g., over 6,000 lbs.).

Similarly the cost of implementing mass reduction may vary depending on the vehicle type. The achieved benefit, in terms of emissions reductions, versus the implementation cost is referred to here as the technology "value". The studies in Table 1.2-1 are representative of the majority of recently published and publicly available mass reduction and cost analysis studies that have been focused on mid-sized passenger cars and cross-over utility vehicles (CUVs). This study was motivated by the recognition that for the large number of vehicles in the full-sized pickup truck segment, customer usage profile and expected duty cycle are significantly different from passenger cars. As a result, simply scaling performance and costs from these studies to truck applications could result in inaccurate estimates.

## 1.2 Analysis Objectives

The primary project objective was to determine the minimum cost per kilogram for various levels of vehicle mass reduction of a light-duty pickup truck, up to and possibly beyond 20%. A maximum 10% increase in total direct manufacturing cost limit was placed as a soft constraint in order to focus the study on more realistic ideas for near-term adoption. The selection criteria for the truck chosen for evaluation specified a mainstream vehicle in terms of design and manufacturing, with a substantial market share in the North American light-duty truck market. Selecting a high-volume, mainstream vehicle increases the probability that ideas generated and their associated costs will be applicable to other pickups trucks in the same market segment.

**Table 1.2-1: Published Passenger Vehicle Mass Reduction and Cost Analysis Studies**

| # | Study | Vehicle Segment | Prime Customer | Prime Contractor | Release Date | Link |
|---|---|---|---|---|---|---|
| 1 | Future Steel Vehicle Phase 1 – Report | Small and Midsize Passenger Cars (Paper Study)† | WorldAuto Steel | EDAG, Inc. | May 2009 | http://c315221.r21.cf1.rackcdn.com/0E091875-143D-4EA8-B070-45CC653A8977/FinalDownload/DownloadId-35434A6571D52C0D3512917F9A290D45/0E091875-143D-4EA8-B070-45CC653A8977/FSV_Phase1_EngineeringStudyReport_05192009.pdf |
| 2 | An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Program | 2009 Toyota Venza | The International Council on Clean Transportation (ICCT) | Lotus Engineering | March 2010 | http://www.theicct.org/sites/default/files/publications/Mass_reduction_final_2010.pdf |
| 3 | Future Steel Vehicle Phase 2 – Report | Small and Midsize Passenger Cars (Paper Study)† | WorldAuto Steel | EDAG, Inc. | April 2011 | http://c315221.r21.cf1.rackcdn.com/FSV-EDAG_Phase2_Engineering_Report.pdf |
| 4 | Light-Duty Vehicle Mass Reduction and Cost Analysis — Midsize Crossover Utility Vehicle | 2010 Toyota Venza | US Environmental Protection Agency (EPA) | FEV North America Inc. | August 2012 | http://www.epa.gov/otaq/climate/documents/420r12026.pdf |
| 5 | Evaluating the Structure and Crashworthiness of a 2020 Model-Year, Mass-Reduced Crossover Vehicle Using FEA Modeling | 2009 Toyota Venza | California Air Resources Board (ARB) | Lotus Engineering | August 2012 | http://www.arb.ca.gov/msprog/levprog/leviii/final_arb_phase2_report-compressed.pdf |
| 6 | Mass Reduction for Light-Duty Vehicles for Model Years 2017–2025 | 2011 Honda Accord | National Highway Traffic Safety Association (NHTSA) | Electricore, Inc. | August 2012 | ftp://ftp.nhtsa.dot.gov/CAFE/2017-25_Final/811666.pdf |

†A paper study was not based on a specific vehicle; rather, on new designs with performance attributes matching production designs in similar vehicle segments.

The scope of work is summarized below along with high level boundary conditions for the analysis. Additional details on the guiding boundary conditions utilized in the mass reduction and costing analyses can be found in Chapter 2.

- Select a mainstream pickup truck, available in the 2011 calendar year, with significant market share in North America. Trucks for consideration should include the Ford F150, Dodge Ram 1500, Chevrolet Silverado 1500, and Nissan Titan

- Select mass reduction ideas that use advanced materials, designs, manufacturing and assembly processes which will likely be available in the 2020-2025 timeframe

- Initially, components and assemblies in all vehicle systems should be assessed for mass reduction. If the ratio of overall mass reduction relative to analysis workload is small, vehicle systems can be discarded from the analysis.

- All direct mass reduction of components (e.g., design and/or material alternatives) as well as mass reduction of components via mass compounding (also referred to as secondary mass savings) are considered viable options. For this project, mass reduction compounding refers to the reduction of mass of a given component as the result of a reduction in the mass of one or several other components.

- Select mass reduction ideas that are production feasible and provide the best value in terms of fixed and variable costs (i.e., maximum direct manufacturing cost increase of 10%).

- Maintain (or improve) the function and performance of the production stock vehicle systems in terms of safety, fuel economy, vehicle utility/performance (e.g., towing, acceleration), NVH, durability, ergonomics, aesthetics, manufacturability, and serviceability.

- Vehicle system/subsystem architecture changes are permitted when existing technology is assumed to be obsolete in the 2017 and beyond timeframe. For example an electronic power steering system replacing the conventional hydraulic system.

- Incorporating system/subsystem architecture changes are not permitted when the replacement technology is potentially a long-term competitor to the baseline technology. For example, replacing the automatic transmission with a dual clutch transmission or replacing the V8 internal combustion engine (ICE) with a downsized V6 ICE with turbocharging and gasoline direct injection. Although some of these alternative technologies may offer a mass reduction, their primary benefit is associated with an overall efficiency improvement. Alternative advanced technologies are considered in separate calculations in EPA's rulemaking modeling.

- Utilize CAE tools as appropriate when comparing baseline vehicle functionalities to the light-weighted design, such as for safety, NVH, powertrain performance, towing, durability, etc.

- Provide comprehensive incremental cost calculations for the mass-reduced vehicle relative to the production stock vehicle, including both detailed direct manufacturing costs (i.e., material, labor and manufacturing overhead) and indirect costs (i.e., end-item scrap, selling, general and administrative [SG&A], profit and engineer, design and testing [ED&T]).

- Develop incremental tooling cost calculations for the mass-reduced vehicle relative to the production stock vehicle.

- The tools and processes to model direct manufacturing costs should be detailed and representative of those used by OEMs and Suppliers in the automotive industry.
- Determine material utilization mix (e.g. steel, plastic, aluminum, magnesium) of production stock vehicle with respect to mass-reduced vehicle.

## 1.3 Consideration of Commercial/Business Factors

As stated previously, the objective of mass reduction and cost analysis was to develop affordable mass reduction ideas which could be adopted into a current conventional pickup truck application. By selecting a mass-production mainstream vehicle in the pickup truck market, the expectation was that many of the ideas generated in the analysis would be universally applicable to similar vehicles in this market segment. The project team recognizes that not all ideas will be suited for every supplier and OEM, including the ideas generated based on the Silverado pickup truck for the Silverado pickup truck. Although feasible from a design and manufacturing perspective, company-, industry-, or business/commercial-related factors may result in an OEM choosing alternative mass reduction technologies (or other vehicle technologies) from those selected in the analysis.

Automotive suppliers and OEMs are routinely making critical business-related decisions aimed at maintaining competitiveness and profitability with current and future products and technologies. Although many of the types of decisions companies are making are universal in nature, the actual decisions and outcomes may differ significantly based on several factors: global manufacturing presence, global market presence, competitive landscape, existing long-term facility and labor contracts, working capital availability, cost of money, existing business partnerships (material suppliers, component suppliers, equipment suppliers, OEMs), existing company policies and culture, consumer market intelligence, company polices on profitability and risk taking, regulatory requirement conformance, and existing technology roadmaps all have an impact on what products and technologies in which suppliers and OEMs will continue to invest.

To minimize the risk of not considering all potential mass reduction opportunities, the team limited the number of business case-type constraints imposed in the analysis. In doing so the team recognizes that different suppliers and OEMs may choose a combination of mass reduction technologies that is different from those ideas selected in this report. Through the process of collecting a wide range of mass reduction ideas beyond those included in the primary vehicle solution, the team anticipates that other combinations of ideas can be assembled offering comparable mass-savings. Some of these alternative ideas are described in Sections 4 and 5.

The team also acknowledges that the business-related factors addressed prior can also have significant impact on light-weighted component costs. The cost analysis portion of the study relies on detailed and transparent cost models adhering to a set of detailed project boundary conditions (e.g., average 450K units/year, mature market conditions, manufacturing in the US, 2012/2013 manufacturing costs/rates, etc.,). The purpose of the cost analysis was not to evaluate what new mass reduction technologies would cost at production inception, but rather to understand how competitive these new mass-reduced component technologies could be in the long-term compared to their existing baseline counterparts, evaluated under the same boundary conditions. If changes to the initial boundary conditions are made (i.e., production volumes lowered, market maturity assumptions modified, etc.), cost model updates would be required to address the differences. Alternatively, learning factors could be applied to account for key cost drivers such as production volumes, technology maturity, and market maturity. In this analysis no attempt is made to understand what the cost of mass reduction would be under alternative sets of boundary conditions.

The component costs calculated in this study are referred to as Net Incremental Direct Manufacturing Costs (NIDMC) and do not include allowances for various OEM indirect manufacturing costs (e.g., production tooling expenses, corporate overhead expenses, research and development expenses, profit, etc.). These expenses are addressed through the application of the EPA’s Indirect Cost Multipliers (ICMs) and are outside the scope of this analysis.

## 1.4 Consideration of Component Mass Reduction On Overall Vehicle Performance

The introduction of any new vehicle technology for increased function, improved performance, and/or reduction in mass, does not come without inherent challenges and risks. Large, dedicated engineering teams at the automotive vehicle manufacturing levels and automotive parts supplier levels spend years developing components for vehicle-specific applications to ensure the designed components meet the component, subsystem, system, and vehicle function and performance specifications. A great deal of this work involves accounting for component interactions (e.g., Noise Vibration Harshness (NVH), durability, corrosion, calibration, etc.).

Due to the nature of this type of project and the inherent analysis limits (e.g. project duration, resources, facilities, funding, etc.), the level of validation which can be conducted on the components within each vehicle system, as well as with assessing the synergistic impact (both positive and negative), is limited. This does not imply that the mass reduction ideas included here are not viable options, or that ideas were included in the primary vehicle solution without some evidence or justification that the necessary technologies could be implemented in the 2020-2025 model year timeframe.

Anticipating that there may be some necessary subsystem/system modifications to correct vehicle performance-level degradation as a result of the negative synergistic impact of component light-weighting, the team implemented a mass and cost counter measure: An NVH counter-measure of 50 kilograms and cost of $150 were added back into the overall vehicle solution. The 50 kilogram NVH countermeasure was based on feedback received by the team on previous light-weighting projects. The $150 on-cost assessment assumed a $3.00 per kilogram cost (50 kg x $3.00 per kg) founded on the team's historical NVH countermeasure cost knowledge.

## 1.5 The Project Team

For the mass reduction and cost analysis project, FEV subcontracted with EDAG and Munro & Associates to create a team with world-class capability, experience, efficiency, and accuracy. As shown in **Figure 1.5-1**, 8 of 19 primary vehicle system/subsystems make up over 85% of a light-duty pickup truck's mass. Out of the 85% vehicle mass, approximately 24% is comprised of powertrain and driveline technology, and 35% is body-in-white and frame and mounting technology. FEV is a technology leader in powertrain and driveline systems, while EDAG is a leader in body-in-white and frame and mounting technology. For remaining systems including suspension, brakes, and interior components (e.g., seats, instrument panel, climate control), the FEV, EDAG and Munro teams provided comprehensive engineering assessments in these areas, backed by a network of industry subject matter experts, ensuring complete, reliable, and transparent results.

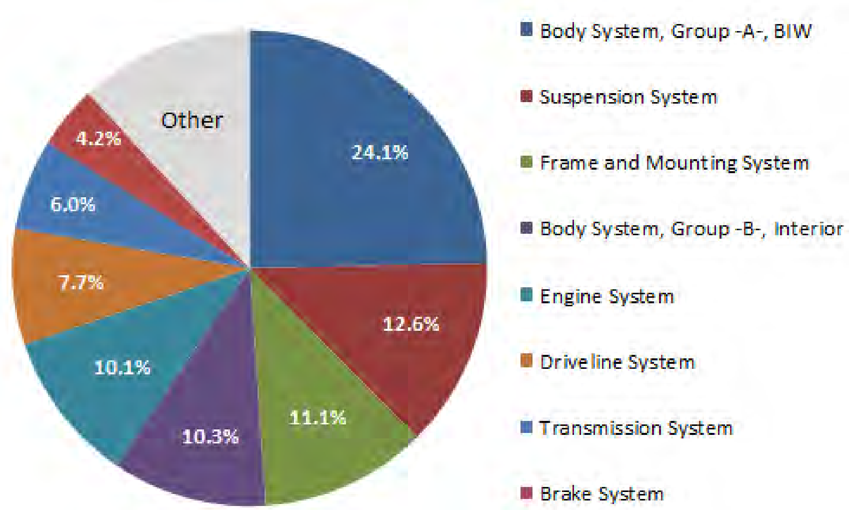



**Figure 1.5-1: Percent Mass Contribution of Light-Duty Pickup Truck, 2011 Silverado**

FEV, along with its partners, have previously worked together on a mass reduction and cost analysis methodology, which was successfully employed on the EPA - 2012 Midsize CUVreport (Report Name: Light-Duty Vehicle Mass Reduction and Cost Analysis - Midsize Crossover Utility Vehicle). The report, detailing the methodology and findings, was published August 2012 and can be found through the following link http://www.epa.gov/otaq/climate/documents/420r12026.pdf.

Following is a brief profile of the three companies that participated in the analysis:

## ***FEV, Inc.***

The FEV Group is an internationally recognized powertrain and vehicle engineering company that supplies the global transportation industry. FEV offers a complete range of engineering services, providing global support to customers in the design, analysis, prototyping, powertrain and transmission development, as well as vehicle integration, calibration and homologation for advanced internal combustion gasoline-, diesel-, and alternative-fueled powertrains. FEV also designs, develops and prototypes advanced vehicle/powertrain electronic control systems and hybrid-electric engine concepts that address future emission and fuel economy standards.

FEV has significant experience in competitive vehicle benchmarking. FEV continues as the competitive engine and vehicle benchmarking supplier for USCAR Engine Benchmarking Group, and the USCAR Transmission Working Group. FEV's benchmarking process is a systematic assessment and characterization of competitive vehicles and powertrains, including detailed analysis, standardized measurements, and standardized test boundary conditions. This allows FEV to accurately compare the particular vehicle system of interest with similar products.

The production development group at FEV is responsible in mass reduction and cost analysis projects of this kind. The core team is comprised of product and manufacturing engineers with an average of 20-plus years in automotive design, manufacturing, and cost engineering. Due to the vast complexity of components and technologies involved in a vehicle, the core team leverages as much internal and external industry support to ensure the mass reduction analysis is robust and defendable. This includes working with Tier 1 component suppliers as well as cutting edge material suppliers (e.g., advance high strength steels, metal matrix composite materials, and carbon fiber composite materials).

The FEV Group employs a staff of over 3,800 highly skilled specialists at advanced technical centers on three continents. FEV North America Inc. employs more than 450 personnel in its North American Technical Center in Auburn Hills, MI.

## ***EDAG, Inc.***

EDAG, Inc. is a U.S. independent engineering partner, developing ready-for-production solutions to ensure the mobility of the future. Because of EDAG's holistic understanding of vehicles and production plants, EDAG offers the fusion of product and production, from development through to serial production, thus creating added value. EDAG's principle of production-optimized solutions is its trademark and a major contribution to the success of its customers. As an all-purpose engineering partner to the international mobility industry, EDAG's vast portfolio includes the development of complete modules, vehicles, and derivatives. Along with providing production-optimized solutions, EDAG, Inc. also holds a prominent position in the fields of electric mobility and lightweight construction. Its expertise and quality standards are found among numerous concepts, concept cars, and technology carriers. This is complemented by further expertise of our global parent company, EDAG Engineering GmbH, regarding model building, prototype construction, and tool and body manufacturing. With their subsidiary FFT, EDAG also provides expertise in the complete development of production plants and factory concepts – from factory, process, and plant development to automation engineering and product cost management. Worldwide, EDAG Engineering GmbH is present on four continents.

***Munro & Associates, Inc.***

Munro & Associates, Inc. is headquartered in Troy, Michigan, with offices in Europe, Canada, and Japan. Munro is a world leader in application and methods of Lean Design®, cost reduction, and quality improvement. Munro provides repeatable methods with consistent metrics that expose, quantify, and predict production and lifecycle cost drivers and risks, as early as the concept phase.

Munro's tools and methods focus on product design. Since the design of a product determines most of a company's costs and rewards, Munro has developed specific tools and standardized metrics to analyze and understand the cost ramifications for all aspects of a design. Munro's Design Profit® accurately calculates total production costs, including the costs of Quality, and even computes a sigma number. Design trade-offs can be quickly analyzed to see the effects on "Total Accounted Costs." Munro's proven methodologies ultimately build business cases that guide their customers to the areas that show the highest returns on investment. Beyond acquisition, Munro also computes total ownership cost, secondary market costs, and impact studies on weight and other key metrics to appreciate end customer benefits against costs.

Munro & Associates' 20,000-square-foot Benchmarking Innovation Center (BIC) is dedicated to reverse engineering and innovative technology transfer. With more than 25 years in business, Munro has developed a state of the art facility and process to get the most out of benchmarking activities.

## 1.6 Structure of This Report

The report is structured in six different sections (including this, Section 1) with Appendices. The sections as they respectfully breakdown include:

**Section 2, Mass Reduction and Cost Analysis Methodology, Tools and Boundary Conditions:** This section provides a detailed review of the methodologies and tools used to generate, select, and validate mass reduction ideas. In addition, the costing modeling methodology, tools and boundary conditions used to establish the direct manufacturing cost differences between the production stock and mass-reduced components is discussed.

**Section 3, Mass Reduction and Cost Analysis Results Overview:** This section provides a vehicle-level overview of the calculated mass reduction and associated costs for each vehicle system. In addition, vehicle system summaries highlighting the mass reduction ideas chosen for major components within each vehicle system are provided. A table at the beginning of each vehicle system summarizes the mass reduction and associated costs at the assembly and subsystem levels.

**Section 4, Mass Reduction and Cost Analyses – Vehicle Systems White Papers:** The vehicle systems whitepaper section provides an in-depth review of the mass reduction ideas and developed costs for each vehicle system. In each system, an overview of the production stock components and technologies is provided. This is followed by an overview of industry trends and mass reduction ideas considered during the analysis. Next, details are provided on the mass reduction ideas selected followed by supporting data on the mass reduction and cost calculations (with and without secondary mass savings). All vehicle system whitepaper sections are organized internally according to subsystems. These subsystems are presented at the beginning of each vehicle system whitepaper section.

**Section 5, Supplementation Analysis:** Additional weight-reduction possibilities developed by the project team, but not implemented in the study, are discussed with regard as to why they were not selected.

**Section 6, Conclusions, Recommendations and Acknowledgements:** The full report summary of primary project objectives, the efforts extended, and the conclusions reached with recommendations for future considerations and actions. Specific consideration is expressed for the invited participants and partners in the study.

**Appendix Section 7.1 System Level Cost Model Analysis Templates (CMATs):** Contains all vehicle system CMATs. The System CMATs provide a subsystem summary of the Net Incremental Direct Manufacturing Costs (NIDMCs) for the production stock (Baseline Technology) and mass-reduced Silverado (New Technology). For each subsystem, primary cost element breakdowns are provided (i.e., material, labor, manufacturing overhead, mark-up).

**Appendix Section 7.2 Body and Frame Supporting Data:** Included here is vehicle scan data, material testing and material models, load path analysis, and study assumptions. Supplementing photos, tables, and graphs regarding the variety of tests and findings are located in this section.

**Glossary of Terms and Initials, Section 8:** Definitions of terms, acronyms, and initials used throughout the report.

# 2. Mass Reduction and Cost Analysis Methodology, Tools and Boundary Conditions

## 2.1 Mass Reduction and Cost Analysis Methodology Overview

The mass reduction and cost analysis project methodology consisted of five general process steps (**Figure 2.1-1**). These same general steps were followed for all 19 vehicle systems. For study purposes, the 19 vehicle systems were categorized into two evaluation groups labelled (1) Powertrain, Chassis, and Trim and (2) Body and Frame.


**Figure 2.1-1: Key Steps in the Mass Reduction and Cost Analysis Project**

**Figure 2.1-2** provides the net amount of component mass considered in each of the evaluation groups. Total starting mass of components evaluated was 2337.5 kg [i.e., as purchased vehicle starting mass (2,454 kg) minus miscellaneous items including fluids, paint, mastic, etc. (116.8 kg)].

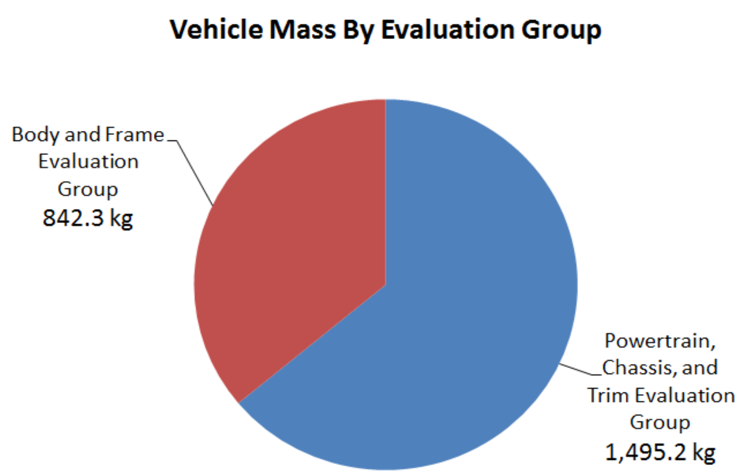



**Figure 2.1-2 Production Stock 1500 Silverado Net Component Mass by Evaluation Group**

The systems and subsystems included in each evaluation group, along with mass contribution for each, are shown in **Figure 2.1-3** (Powertrain, Chassis, and Trim) and **Figure 2.1-4** (Body and Frame). Note as shown in Figure 2.1-4 there were a few components (e.g., tow provisions, isolators, liners and covers) which belong to the body and frame vehicle systems, though were evaluated by FEV.

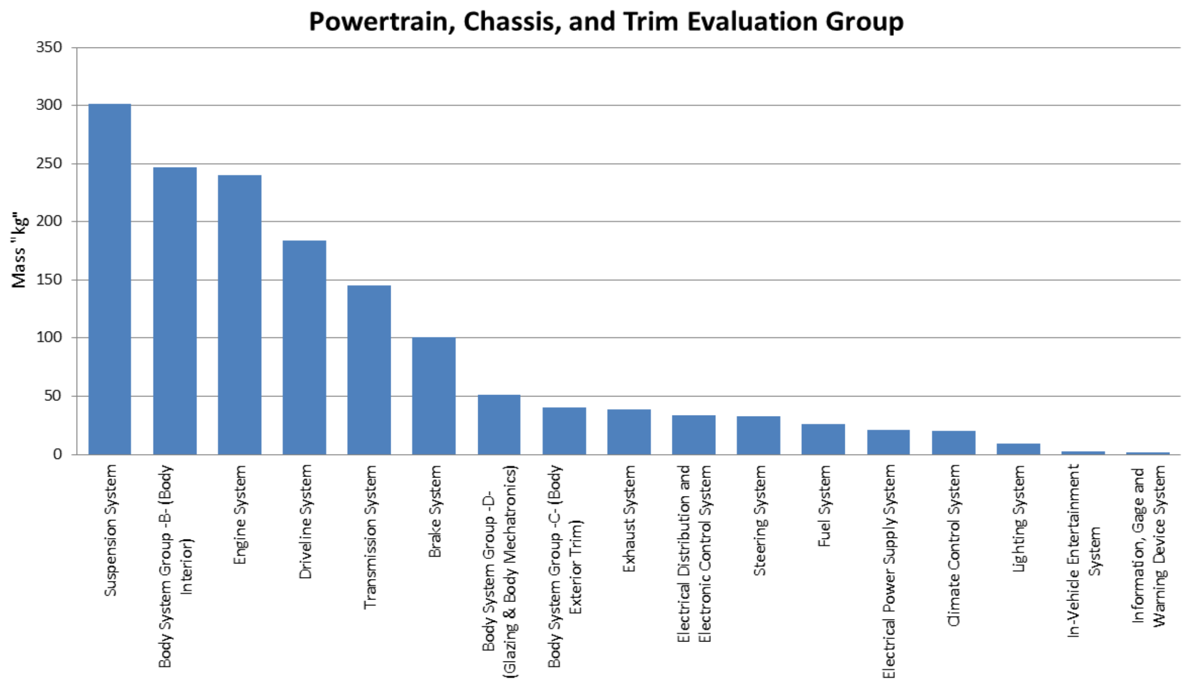



**Figure 2.1-3: Key Systems in Powertrain, Chassis and Trim Evaluation Group**

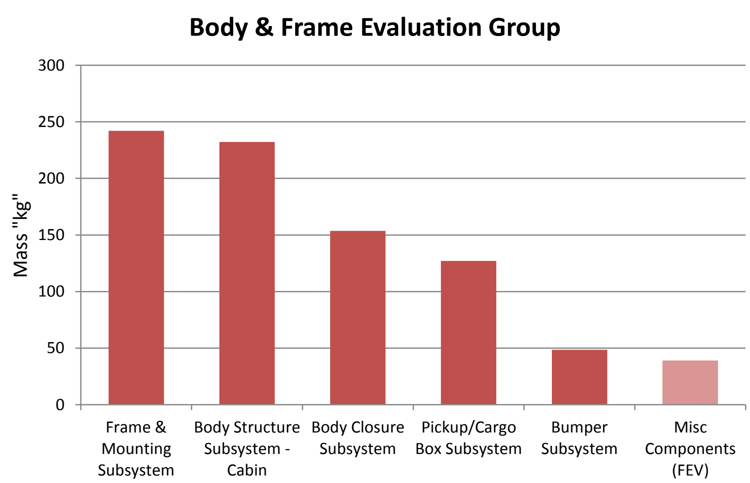



**Figure 2.1-4: Key Systems and Subsystems Included in Body and Frame Evaluation Group**

The Powertrain, Chassis, and Trim Evaluation Group consists of 17 vehicle systems. In general, all seventeen systems were treated independently in terms of mass reduction assessment and validation. This approach has some inherent shortcomings as the impact of mass reduction at systems interfaces is neglected. A complete vehicle CAE analysis to assess the system interactions in terms of vehicle performance attributes such as handling, steering, braking, stiffness, and NVH is a significant undertaking and was outside the scope of this analysis. Recognizing mass reduction countermeasures would likely be required to refine mass reduction concepts and offset negative system interactions, the team added 50 kilograms of mass back into the mass-reduced vehicle at a cost of $150. The FEV and Munro team led the mass reduction and cost analyses for the Powertrain, Chassis and Trim evaluation group.

The Body and Frame Evaluation Group consists of two vehicle systems, Body System Group -A- (body-in-prime/body-in-white components, assemblies and subsystems) and Frame System. The body and frame vehicle systems provide many functions with respect to the overall vehicle performance. One major function is maintaining occupant safety under varying vehicle crash conditions. A major concern with light-weighting is the potential adverse impact it may have on vehicle crash performance and occupant safety. To ensure the crash integrity of light-weighted vehicle concept was maintained relative to the baseline vehicle, the body and frame systems incorporated substantially more CAE modeling and validation than all remaining vehicle systems. Also, due to the synergistic characteristics of the body and frame in terms of crash, NVH (noise, vibration, and harshness), payload, towing, etc., it was judicious to evaluate these two systems together. Closures were evaluated for stiffness, oil canning, and residual deformation. To address the unique characteristics and requirements of full-size pickups, durability performance was evaluated for the frame, and simulation of the full-vehicle dynamic performance was performed. The EDAG team led the evaluation of the frame and body systems.

The primary process steps were the same for both evaluation groups. At a subtask level, methods and tools employed for each evaluation group were customized to meet project objectives. To clearly present the methodology, tools and analysis assumptions, the remainder of Section 2 is subdivided into two sections: Section 2.2: Powertrain, Chassis and Trim; and Section 2.3: Body and Frame.

## 2.2 Powertrain, Chassis and Trim Mass Reduction Evaluation Group – Methodology Overview

Sections 2.2.1 - 2.2.5 provide details on the subtasks performed, and tools utilized, for each of primary process steps identified previously in **Figure 2.1-1**. In the initial analysis no mass-compounding/secondary mass-savings were assumed as part of the vehicle system evaluations. To account for secondary mass reductions Step 5 was repeated for those systems impact by overall vehicle mass reduction (i.e., Engine, Transmission, Suspension, Brake, Exhaust and Fuel).

### 2.2.1 Step 1: Baseline Vehicle Fingerprinting


**Figure 2.2-1: Key Steps in Baseline Vehicle Fingerprinting**

The process began with the purchase of the baseline vehicle, a 2011 Chevrolet Silverado.

Before vehicle disassembly, key vehicle measurements were taken, including the four corner vehicle weight, vehicle ground clearance, and noted positions of key components (e.g., engine, fuel tank, exhaust) as assembled in the vehicle relative to the center of the front tires.

Following the vehicle measurements, a systematic, detailed vehicle disassembly process was initiated. The vehicle disassembly was initially completed at a high level (e.g., engine-transmission assembly, door assemblies, rear-hatch assembly, seats, exhaust assembly). At each stage of the disassembly process, the same order of events took place: 1) process mapping of part(s) to capture the part removal process (inverse-part assembly process); 2) photographing of part as assembled and as removed from the vehicle; and 3) initial part attributes (i.e., part weight and quantity). As each part was removed from the vehicle, it was logged into a general vehicle-level Comparison Bill of Material (CBOM).

As part of the initial teardown process white-light scanning (WLS) was not conducted. The starting point for the vehicle CAE model was an existing model of a 2007 Silverado that was completed for a study of advanced plastics and composites technologies by the National Crash Analysis Center (NCAC) at George Washington University, with Consulting LLC, and University of Dayton Research Institute to NHTSA. The EDAG team evaluated differences between the 2007 CAE model and actual 2011 purchased baseline vehicle. Where differences existed, WLS was judiciously implemented to update the 2007 CAE model to a 2011 version. Additional details on the methodology and updates made can be found in Section 2.3, "Body and Frame Mass reduction Evaluation Group – Methodology Overview."

After the vehicle was completely disassembled, major modules were further broken down into respective system groups. For example, the components within the front suspension module (e.g., brake rotors, control arms, differential, suspension struts, springs) were removed from the module and grouped in their respective systems (**Image 2.2-1**). A process similar to the vehicle disassembly process was followed to ensure applicable information was captured (e.g., weight, geometric size, process map, photographs) and recorded for each component. During this step, system CBOMs were created. All components belonging to a system (e.g., engine, transmission, body, brakes, fuel) were physically grouped together and captured together in the system CBOM.

**Image 2.2-1: 2011 Chevrolet Silverado Front Suspension Module as Removed During the Teardown Process**
*(Source: FEV, Inc.)*

### 2.2.2 Step 2: Mass Reduction Idea Generation


**Figure 2.2-2: Key steps in Mass Reduction Idea Generation**

Upon completion of assembly part binning and tracking, a parallel and iterative process of teardown and mass reduction idea generation was initiated. In general, the assembly level teardown involved a full, detailed disassembly of parts into the lowest level manufactured component forms. This involved both destructive and non-destructive teardown processes. For example, the Front Strut Assembly (**Image 2.2-2**) was fully disassembled down to the individual manufactured components. From this detailed teardown, an accurate assessment of the component materials, weights, hidden design details, and manufacturing processes utilized to manufacture the production stock Silverado front strut assembly were collected. At all teardown levels, the CBOMs were updated, thereby tracking key component information (e.g., parts, quantities, weights).

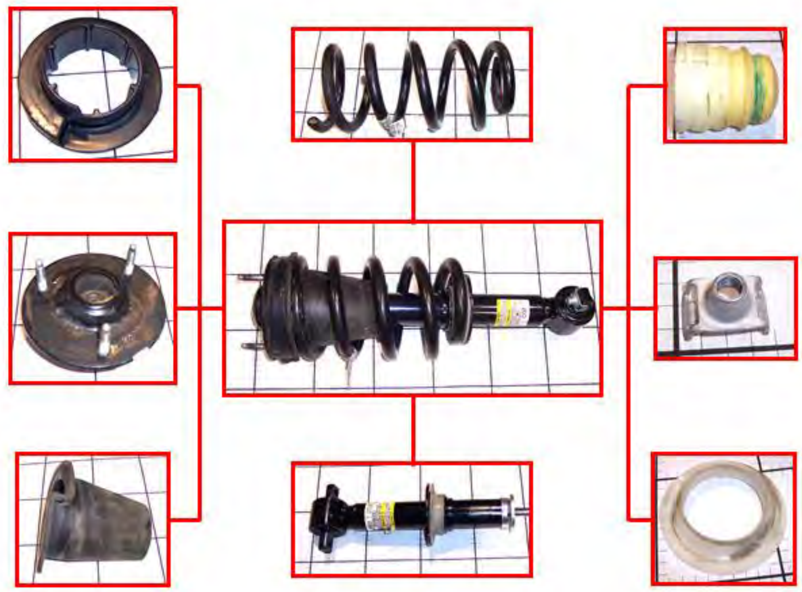


**Image 2.2-2: Chevrolet Silverado Front Strut Assembly Disassembled**
*(Source: FEV, Inc. photos)*

In parallel to hardware being disassembled, vehicle system leads (i.e., project engineers responsible for generating mass reduction ideas for a particular vehicle system) began the mass reduction idea generation process. The process began with logging individual ideas into the FEV Brainstorming Template (FBT). The FBT contained five major sections:

- Part 1: General Part Information Entry
- Part 2: Mass Reduction Idea Entry
- Part 3: Primary Idea Ranking and Down-Selection Assessment
- Part 4: Quantitative Mass Reduction and Cost Analysis Estimation Entry
- Part 5: Final Ranking and Down-Selection Process Assessment

In this initial idea generation phase of the analysis, Parts 1 and 2 of the brainstorming template are completed. As shown in **Figure 2.2-3,** several sources were utilized for gathering mass reduction ideas, including automotive vehicle manufacturers, automotive parts suppliers, raw material suppliers, benchmarking suppliers, and non-automotive part design and manufacturing technologies. The medium for attaining the information came from published articles, papers and journals, supplier websites, supplier published presentation materials, consultation with suppliers, access to benchmark databases (FEV internal, Munro & Associates internal, EDAG internal, A2MAC1 purchased subscription), and internal brainstorming storming sessions. In **Section 4, "Mass reduction and Cost Analysis – Vehicle System White Papers,"** a significant amount of the details supporting the mass reduction ideas are captured (e.g., sources of information, applications in production, manufacturing process details).

At this point, teams began reviewing the baseline design and the materials being used for each component in their respective, individual systems. This was done to compare systems with known technologies already available.

A significant number of the mass reduction ideas presented in this report are based on implementation of "off-the-shelf" technologies. These are technologies which are either mature mass-produced technologies already implemented by several OEMs on multiple vehicle platforms, or to a lesser degree new low-volume production technologies that have been selectively released due to a low maturity level and/or incremental cost increase. By selecting mass reduction ideas that are already in production and/or have gone through significant research and development by OEMs, automotive parts suppliers, and/or automotive raw material suppliers, the implementation risk and manufacturing feasibility risk are considered far less. The end result is a list of ideas with high probability of implementation success.

In almost all cases, assumptions were required to take the mass reduction ideas from surrogate components and transfer them to Chevrolet Silverado-specific components. This included normalizing the surrogate parts sizes and weights to Chevrolet Silverado specific parts, and when required, making high-level mass adjustments for considerations to design and applications differences. No detailed calculations or CAE analysis was initiated at this stage.

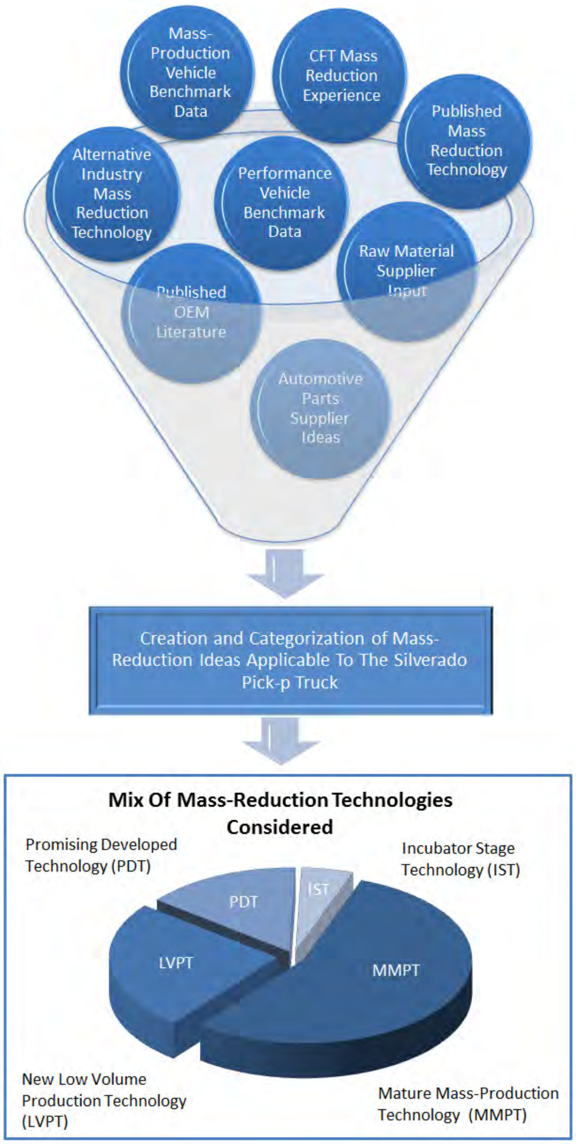



**Figure 2.2-3: Sources of Information Used to Develop Mass Reduction Components**

In addition to "off-the-shelf" ideas, a brainstorming process was employed to explore a broader range of mass reduction ideas. Participants were encouraged to focus on creating many ideas and cautioned not to pre-judge anything, since even ideas that initially seem outrageous can spawn new ideas that are more feasible. The critiquing process would take place afterward, during the idea ranking process. Participants were also encouraged to consider new design concepts that would allow for part elimination, particularly fasteners and brackets. Oftentimes several independent ideas could be combined into a single workable idea. Finally, the participants were encouraged to consider new materials, including inspirations from outside the automotive industry.

Many ideas generated often appear unconventional, but with additional engineering analysis and research, the ideas are either eliminated from the list or take root and become feasible. One such idea, from the Venza study, was an all-aluminum brake booster. While the idea initially seemed far-fetched, Continental announced in March 2013 that it was offering an all-aluminum brake booster that "reduced weight and has a shorter overall length."

**Figure 2.2-3** shows the approximate mix of mass reduction ideas considered relative to maturity status. The actual mix was very vehicle system dependent. Additional information on the maturity of technologies considered for each system can be found in Section 4.

Upon completion of the idea generation phase, the preliminary idea ranking and down-selection process began. While evaluating the proposed ideas, the engineering team faced two major concerns: First, whether the idea will perform to the vehicle's specifications. The second concern is whether the cost will be prohibitive or not. In Part 3 of the brainstorming template, the ideas were scored according to the cost, benefit, and risk of implementation using a five parameter ranking system: 1) Manufacturing Readiness Risk, 2) Functionality Risk, 3) Estimated Percent Change in Weight, 4) Estimated Change in Piece Cost, and 5) Estimated Change in Piece Cost as a Result of Tooling. As shown in **Figure 2.2-4**, there were predefined scoring values for each parameter. The ratings for each category were pre-weighted to account for variation in importance among categories.

| Numbering | | Part Name/Description | | Part 3: Primary Idea Down-Select Scoring Process | | | |
|---|---|---|---|---|---|---|---|
| Subsystem | Sub-Subsystem | Subsystem | Idea Description | Manufacturing Readiness Risk<br>"Possible for 2025 Timeframe"<br>< 1 > High Production Automotive<br>< 2 > High Production Other<br>< 3 > Low Production<br>< 5 > Still In Development/R&D | Functionality Risk (Drivability, Performance, Crash)<br>"Will it work"<br>< 1 > Equal or Better<br>< 2 > Vehicle Ancillary Function Degrade<br>< 5 > Vehicle Minor Primary Function Degrade<br>< 10 > Vehicle Major Primary Function Degrade | Estimated Percent Change In Weight<br>< 1 > 20% or Greater Decrease<br>< 2 > 10-20% Decrease<br>< 3 > 0-10% Decrease<br>< 10 > Weight Increase | Estimated Percent Change In Piece Cost<br>< 1 > No Change or Decrease<br>< 2 > 0-10% Increase<br>< 3 > 10-25% Increase<br>< 7 > > 25% Increase |
| | | | **Individual Rotor Ideas** | | | | |
| 03 | 01 | Front Rotor/Drum and Shield | Vent (slot) front rotors | 1 | 1 | 3 | 2 |
| 03 | 01 | Front Rotor/Drum and Shield | Cross-Drill front rotors | 1 | 1 | 3 | 2 |
| 03 | 01 | Front Rotor/Drum and Shield | Two piece Rotor - Al light-weight center (hat) with Iron/Steel/CF outer surface (disc) w/ T-nut fasteners | 2 | 1 | 1 | 3 |
| 03 | 01 | Front Rotor/Drum and Shield | Change Material for Rotors - Al/MMC | 3 | 1 | 1 | 7 |
| 03 | 01 | Front Rotor/Drum and Shield | Downsizing based on Rotor fins added to hat | 1 | 1 | 3 | 3 |
| 03 | 01 | Front Rotor/Drum and Shield | Clearance drill holes in rotor top hat surface to reduce wt | 2 | 1 | 3 | 2 |
| 03 | 01 | Front Rotor/Drum and Shield | Drill holes in rotor hat perimeter | 3 | 1 | 3 | 2 |
| 03 | 01 | Front Rotor/Drum and Shield | Chg from straight to directional vanes btwn rotor disc surfaces (5%) | 3 | 1 | 3 | 2 |
| 03 | 01 | Front Rotor/Drum and Shield | Replace from comparable A2MAC1 database | 1 | 1 | 1 | 1 |
| 03 | 01 | Front Rotor/Drum and Shield | Change Material for Rotors - Carbon Ceramic | 3 | 1 | 1 | 7 |

**Figure 2.2-4: Primary Idea Down-Select Process Excerpt from FEV Brainstorming Template**

Manufacturing Readiness Risk

The Manufacturing Readiness Risk is a numerical value ranging from low risk (1) for ideas already used in the automotive industry at high production levels, to higher risk ideas used at low production levels (3), to ideas still in development (5). The High Production ideas are those components that can be found in high-production vehicles. Components such as aluminum knuckles, aluminum control arms, and plastic fuel tanks offer minimal risk in terms of manufacturability readiness. The Low Production ideas are those components that can be found in low-production vehicles such as magnesium transmission cases, aluminum body closures, composite leaf springs, etc. and therefore have moderate implementation risk. The “still in development” ideas have no current production examples to which to be compared and therefore carry the most risk in terms of manufacturing readiness.

Functionality Risk

The Functionality Risk is a numerical value which assesses the potential functional degradation of the mass-reduced part (e.g. crash, NVH, braking). The goal in the analysis was not to have any primary functional degradation with mass reduction. A mass-reduced part which was estimated to meet or exceed primary function scored a one (“1”). Conversely, if the mass reduction resulted in a notable functional degradation, it scored a ten (“10”).

The team felt it important not to discount items that may result in minor primary function degradation in the initial scoring. The thought was that these ideas may have the potential to overcome functional degradation concerns by making further component modifications and/or systems changes. Providing a score of five (“5”), with all other categories scoring favorably, would promote the idea to the next scoring round. If the scoring worked out favorably in the next step, additional work would be performed to determine if any further changes could be made to equalize primary functionality relative to the baseline.

The team also realized that some mass reduction initiatives may maintain primary function, although may have actual or perceived ancillary/secondary degradation. For example, as some assemblies or components within are made lighter, their tactile feel changes, which may generate an initial perception of “cheapness” by the end consumer. Types of components which fall into this group generally include driver interface components such as door handles, console control knobs, interior trim panels, plastic throttle pedals, and shifters. A lighter aluminum hood that has a different feel and audible noise when closing may also generate a similar perception. In situations like these, if the team felt an ancillary/secondary functional degradation was potentially possible (actual or perceived), they scored the idea with a two (“2”).

Mass Impact

Mass Impact is a numerical value based on expected percentage change in mass comparing the redesigned mass to the baseline mass. There were four categories from which the idea could be scored: “20%+ Mass Reduction,” “10-20% Mass Reduction,” “0-10% Mass Reduction,” or “Mass Increase.”

Cost Impact

Cost was also taken into consideration when scoring an idea as to whether the new design is less than, equal to, or greater than the baseline cost. The Cost Risk value is a weighted number based on the expected percent of change in cost comparing the redesign cost to the baseline cost. There were four categories from which the idea could be scored: “Same or Less Cost,” “0-10% Cost Increase,” “10-20% Cost Increase,” or “20%+ Cost Increase.”

Tooling Impact

Tooling Impact is a weighted number based on expected piece cost impact associated with changing from the baseline component tooling to the redesigned component tooling. There were three categories from which the idea could be scored. Either the idea was the “Same Part Cost or Decreased Part Cost,” “0-25% Part Cost Increase,” or “25%+ Part Cost Increase.”

Idea Total Score

The Idea Total Score is derived by multiplying each of the five scoring parameter values together. The resulting value is then used to determine which among the many ideas will be advanced to the next level of review.

The range of values for each individual parameter was set considering the importance relative to the other parameters. The final idea score is the multiple of the five parameter rankings. The best possible score is “1” (i.e., 1x1x1x1x1), which is representative of an idea already in high automotive production, performs equal-to or better-than the current production Silverado part, is expected to yield a 20% mass reduction, and is cost-neutral or a saving relative to the current production piece cost and tooling.

The highest achievable value is 10,500 (i.e., 5x10x10x7x3) which represents the opposite extreme. The majority of the mass reduction ideas selected were conservative, thus resulting in a score between 1 and 200. A score of 50 was chosen as the cut-off for the initial down-selection process. Any mass reduction ideas with a value greater than 50 were removed from the analysis; although, there were a few exceptions, dependent on the number of ideas for a given system.

Ideas that had an initial score of less than 50 were considered high probability mass reduction ideas. For each of these ideas which made the first cut, the project team then estimated the potential mass reduction and cost impact of each idea using an FEV developed mass and cost calculator tool. This Excel-based calculator (**Figure 2.2-5**) was created as a quick way to analyze basic baseline component data and return a baseline component cost, redesigned component cost, and a redesigned component mass. While the Idea Scoring Number helped sort-out ideas quickly based on the teams experience, knowledge, and discretion, the mass and cost calculator took actual baseline component data (i.e., component mass, material, load type, and manufacturing processes) and evaluated it against the redesign component data to yield a cost/kg delta. This provided a more objective measure of value (cost per kilogram) for those mass reduction ideas meeting the initial score criteria. In addition the calculated data was used to monitor cumulative mass reduction potential and the cumulative cost increase as individual ideas were combined to create final mass reduction solutions.

| BASE TECHNOLOGY | |
|---|---|
| Material | Cast Iron (ASTM A-48) |
| Material $/kg | 1.32 |
| Material Content/Pc Price Ratio | 60% |
| Component Loading Application | Blend |
| Density (g/cm^3) | 7.929 |
| **Part Mass (kg)** | **4.803** |
| Part volume (cm^3) | 605.8 |
| Material Cost/pc | 6.351 |
| **Total Cost** | **10.586** |

| NEW TECHNOLOGY | |
|---|---|
| Material | Aluminum (2014-T6) |
| Material $/kg | 3.84 |
| Material Content/Pc Price Ratio | 70% |
| Component Loading Application | Blend |
| Density (g/cm^3) | 2.669 |
| **Part Mass (kg)** | **2.343** |
| Part Redesign Mass Delta | 0.000 |
| Part volume (cm^3) | 557.5 |
| Volume Ratio (new/old) | 0.92 |
| Material Cost/pc | 8.997 |
| **Total Cost** | **13.813** |

| | |
|---|---|
| Mass (old-new) | 2.460 |
| Cost (old-new) | ($3.23) |

**Approx Mfg Ratios:**
**(Mat'l to Burden/Labor Content)**

Assembly, Automated - 40%
Manual - 50%
Semi-Auto - 60%

Bending, CNC - 50%
Fixed - 60%

Casting, Die - 70%
Sand - 60%

Forging - 65%

Heat Treat - 35%

Machining, CNC - 75%
Dedicated - 65%
Grinding - 70%
Honing/Lapping - 70%

Molding, Metal Injection - 60%
Plastic Injection - 50%
Powder Metal - 45%

**Figure 2.2-5: FEV Mass and Cost Calculator Example**

The mass calculations within the calculator are based on mathematical formulas for bending strength, bending stiffness, and blend (50%-50%). The user must enter the baseline part material, baseline part mass, and the type of process used to manufacture the part (Material Content/Pc Price Ratio). The Material Content/Pc Price ratio is dependent on the type of process used to manufacture the part, and is expressed as the proportion of total piece price relative to material costs. For example, the manufacturing cost of a sand casted part is approximately 60% material and 40% processing (calculations do not include mark-up). The Mass & Cost Calculator has processing ratios for all the different types of processes used, however, only a small subset is shown previously in **Figure 2.2-5**. Finally, the user must also enter the type of material being used for the redesigned or "New Technology" component as well as the type of process (Material Content/Pc Price Ratio) used to manufacture the redesign part.

The calculator also has an expandable database from which the mechanical properties of the baseline and redesign materials are stored. The user must select the mechanical load type (Component Loading Application) for which the part is subjected (Bending Strength, Bending Stiffness, Blend). The calculator algorithms looks-up the baseline material properties and compares those with the redesign material properties as well as the mechanical load type and returns an estimated mass required to make the redesigned component equal in performance to the baseline design.

The material database contains many of the common materials used in the automotive industry, included up-to-date material costs. Once the calculator has determined the redesign mass, it returns a cost estimate based on the material type, amount of material and the type of process used to manufacture the part (i.e., die-casting, sand casting, injection molding, etc.).

It should be re-emphasized that the Mass and Cost calculator only provides budgetary estimates for initial comparison. During the final step in the project analysis (Step 5, Detailed Mass reduction Feasibility and Cost Analysis) higher fidelity mass and cost calculations are performed on the final mass reduction ideas selected for each vehicle system.

The mass reduction and cost calculations are added beside each relevant idea in the FEV brainstorming matrix (Part 4 of the matrix). Using the calculated mass, calculated cost impact, and Idea Total Score Number (Part 3 of FBT), cost-versus-mass and total score-versus-mass calculations are made (**Figure 2.2-6**). The calculated values, found in Part 5 of the brainstorming template, are used in the final down-selection process when comparing competing mass reduction ideas on a similar part.

In many cases team members considered together the preliminary rankings (Part 3 of FBT), the magnitude of the mass reduction savings (Part 4 of the FBT), and the value of the mass reduction ideas (Part 5 of the FBT) to determine the final mass reduction ideas to move forward at the component and assembly level.

| Part Numbering | | | Part Name/Description | | Part 3: Primary Idea Down-Select Scoring | Part 4: Estimate Weight and Cost Impact on "Best Scored Idea(s)" | | Part 5: Using Idea Total Score, Unit Weight Save Cost, and Score/Incremental Weight Change, Identify Concept for Evaluation | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Subsystem | Idea Description | Idea Total Score<br>Low Ranking = High Potential Solution<br>High Ranking = Low Potential Solution | Estimated Incremental Weight Change "kg" | Estimated Incremental Piece Cost Impact "$" | Unit Weight Save Cost "$/kg" | Scoring/Incremental Weight Change<br>"Total Score/kg" |
| | | | | **Individual Rotor Ideas** | | | | | |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Vent (slot) front rotors | 6 | 0.114 | -4.40 | -$38.52 | 52.55 |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Cross-Drill front rotors | 6 | 0.498 | -3.47 | -$6.98 | 12.04 |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Two piece Rotor - Al light-weight center (hat) with Iron/Steel/CF outer surface (disc) w/ T-nut fasteners | 12 | 3.520 | -5.57 | -$1.58 | 3.41 |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Change Material for Rotors - Al/MMC | 42 | 8.224 | -48.85 | -$5.94 | 5.11 |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Downsizing based on Rotor fins added to hat | 18 | 0.395 | 0.87 | $2.20 | 45.62 |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Clearance drill holes in rotor top hat surface to reduce wt | 12 | 0.224 | -1.63 | -$7.27 | 53.53 |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Drill holes in rotor hat perimeter | 18 | 0.199 | -0.92 | -$4.63 | 90.33 |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Chg from straight to directional vanes btwn rotor disc surfaces (5%) | 36 | 0.689 | 1.52 | $2.20 | 52.25 |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Replace from comparable A2MAC1 database | 1 | 0.977 | 2.15 | $2.20 | 1.02 |
| 06 | 03 | 01 | Front Rotor/Drum and Shield | Change Material for Rotors - Carbon Ceramic | 42 | 9.799 | -106.38 | -$10.86 | 4.29 |

Note: Negative Cost In Template Represents Cost Increase ( i.e., Cost of Base Technology minus Cost of New/Mass-Reduced Technology )

**Figure 2.2-6: Estimated Weight and Cost Impact (Part 4) and Final Ideal Down-Selection (Part 5) Excerpt from FEV Brainstorming Template**

Upon completion of the final down-selection process, mass reduction ideas are grouped/binned together based on their value (cost per kilogram). There are five cost groups total, plus one group for tracking "decontenting" ideas that reduce mass, but at the sacrifice of function and/or performance (**Figure 2.2-7**). Decontenting ideas are tracked in the analysis but never included in the final calculations.

At this stage of the analysis, the mass reduction ideas captured are not necessarily complete mass-reduced components or assembly solutions, as several ideas can be combined to formulate a component or assembly solution. The process of combining ideas occurs in the next phase of the analysis, which is referred to as the mass reduction optimization phase.

IDEA GROUPING

●Five cost groups were established to group ideas based on their average cost/kilogram weight save:

Level A: ≤ \$0.00/kg (i.e., ideas that either save money or add zero cost)
Level B: >\$0.00 to ≤ \$1.00
Level C: >\$1.00 to ≤ \$2.50
Level D: >\$2.50 to ≤ \$5.10
Level X: > \$5.10

● One additional category exists, which is independent of the cost per weight save ratio. This sixth category is referred to as the "Decontenting" category (Level Z) and is reserved for ideas which degrade a systems function/performance by employing the mass reduction idea.

● Decontenting can occur at various functional levels: (1) comfort convenience components (e.g. cup holders, DVD player, storage concealer), (2) secondary support components (e.g. spare tire, jack), or (3) at a primary function level (e.g. downsized engine w/ less horsepower)

**Figure 2.2-7: Mass Reduction Idea Grouping/Binning Based on Mass Reduction Value**

### 2.2.3 Step 3: Mass Reduction and Cost Optimization Process


**Figure 2.2-8: Key steps in Mass Reduction and Cost Optimization Process**

The next step in the process is to take the down-selected mass reduction ideas and formulate feasible and economically viable mass-reduced component, assembly and subsystem solutions. To organize the potential component/assembly and subsystem mass reduction solutions, the same cost groups shown in **Figure 2.2-7** are utilized. The end objective is to provide a selection of subsystem mass reduction solutions, at varying levels of cost (cost per kilogram), for each vehicle system. In the subsequent analysis step (Step 4), Selection of a Vehicle Mass Reduction Solution, the various subsystems solutions are evaluated against one another at the vehicle level to determine which subsystems offer the best value in terms of creating a mass-reduced vehicle solution.

To help explain the optimization methodology, a brake system example will be used as the reference system. The same process is employed for all vehicle systems. The starting point is combining mass reduction ideas into various component and assembly mass-reduced options. Shown in **Figure 2.2-9**, the front rotor has nine different ideas which can be combined into several different combinations to create different mass-reduced rotors with different cost impacts (cost per kilogram). Note, not all ideas can be combined together, as some are alternative options within the same or different cost group. Similar to how mass reduction ideas are grouped/binned into different value groups, the sample methodology applies to components/assemblies, subsystems, and systems.

| Mass-Reduction => Mass-Reduced Component/Assembly Options (Example: Front Rotor) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Cost Group: A | | Cost Group: B | | Cost Group: C | | Cost Group: D | | Cost Group: X | |
| Range "$/Kg" | ≤ $0 | Range "$/Kg" | >$0.00 - ≤ $1.00 | Range "$/Kg" | >$1.00 - ≤ $2.50 | Range "$/Kg" | >$2.50 - ≤ $5.10 | Range "$/Kg" | >$5.10 |
| Idea #1 Downsize based on comperable vehicle | | | | Idea #2 Vent/Slot Rotor | | Idea #1 Downsize based on comperable vehicle | | Idea #2 Vent/Slot Rotor | |
| | | | | Idea #3 Cross Drill Rotor | | Idea #2 Vent/Slot Rotor | | Idea #3 Cross Drill Rotor | |
| | | | | Idea #4 2-Piece Rotor | | Idea #3 Cross Drill Rotor | | Idea #4 2-Piece Rotor | |
| | | | | Idea #5 Change Rotor Mtl to AL/MMC | | Idea #4 2-Piece Rotor | | Idea #6 Drill Clearance Holes in Top Hat | |
| | | | | Idea #6 Drill Clearance Holes in Top Hat | | Idea #5 Change Rotor Mtl to AL/MMC | | Idea #7 Directional Vanes | |
| | | | | | | Idea #6 Drill Clearance Holes in Top Hat | | Idea #9 Change Rotor Mtl to Carbon Ceramic | |
| | | | | | | Idea #7 Directional Vanes | | | |
| | | | | | | Idea #8 Drill Holes in Hat Perimeter | | | |

**Figure 2.2-9: Component/Assembly Mass Reduction Optimization Process**

Each team grouped as many individual ideas together as possible in order to obtain the greatest mass savings while staying within the cost range for each cost group. The intent is to try and have a component mass reduction solution for every cost group (A, B, C, D, X). Though having a solution for every cost group was dependent on the number of ideas passed through following the initial idea generation and down selection process.

The next step is to combine component and assembly solutions into subsystem solutions. Shown in **Figure 2.2-10**, the same methodology for combining mass reduction ideas into component/assembly solutions is used for combining components/assemblies into brake subsystems. In the case of the Front Rotor/Drum and Shield Subsystem, three groupings of components and assemblies created three different subsystem cost solutions. Various component and assemblies solutions from cost groups A, B, and D were combined to create a subsystem solution in cost groups A, B, and C. The process is repeated for the remaining subsystems (e.g., Rear Rotor/Drum and Shield Subsystem, Parking Brake and Actuation Subsystem, Brake Actuation Subsystem, Power Brake Subsystem).

| | Mass-Reduction => Mass-Reduced Subsystem Options (Example: Brake System) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cost Group: A | | Cost Group: B | | Cost Group: C | | Cost Group: D | | Cost Group: X | |
| Subsystems | Range "$/Kg" | ≤ $0 | Range "$/Kg" | >$0.00 - ≤ $1.00 | Range "$/Kg" | >$1.00 - ≤ $2.50 | Range "$/Kg" | >$2.50 - ≤ $5.10 | Range "$/Kg" | >$5.10 |
| Front Rotor/ Drum & Shield | Rotor - A<br>Brake Shield - D<br>Caliper Housing - B<br>Pad Kit - A<br>Caliper Brkt - B | | Rotor - C<br>Brake Shield - D<br>Caliper Housing - B<br>Pad Kit - A<br>Caliper Brkt - B | | Rotor - D<br>Brake Shield - D<br>Caliper Housing - B<br>Pad Kit - A<br>Caliper Brkt - B | | | | | |
| Rear Rotor/ Drum & Shield | | | | | Drum - A<br>Backing Plate - D<br>Guide Plate - A<br>Brake Shoes - A<br>Actuation Lever - D<br>Wheel Cylinder - D | | Drum - D<br>Backing Plate - D<br>Guide Plate - A<br>Brake Shoes - A<br>Actuation Lever - D<br>Wheel Cylinder - D | | | |
| Parking Brake & Actuation | | | | | Parking Brake Lever & Frame - C | | | | | |
| Brake Actuation | | | | | Accelerator Pedal - A<br>Brake Pedal Arm - B<br>Brake Pedal Pad - A<br>Brake Pedal Brkt - D<br>Brake Pedal Frame - C | | | | | |
| Power Brake | | | | | Booster Shell Front - C<br>Booster Shell Rear - C<br>Piston, Actuator - C<br>Studs - MC to BM - D<br>Studs, Booster - D<br>Pivot Shaft - X<br>Backing Plate (F) - C<br>Backing Plate (R) - C<br>Backing Plate (S) - C | | | | | |

**Figure 2.2-10: Subsystem Mass Reduction Optimization Process**

### 2.2.4 Step 4: Selection of Vehicle Mass reduction Solution

As stated in Section 1, the primary project objective was to determine the minimum cost per kilogram for light-weighting a light-duty pickup truck, at various levels of vehicle mass reduction. To accomplish this objective consideration of the best value solutions within a subsystem, and best value subsystems with the vehicle must be evaluated simultaneously. A vehicle level subsystem matrix was used to capture all the derived subsystem solutions. Although the subsystems are grouped by vehicle system, there selection and integration into a vehicle level mass reduction solution were treated independently unless subsystem interdependency existed (i.e., Subsystem 1 mass reduction is impacted by Subsystem 2 mass reduction). In the analysis subsystem dependencies were minimized by grouping interdependent components in the same subsystem.

The process of arriving at the final vehicle mass solution was somewhat of an iterative process. It started by first selecting all subsystems available in Cost Group A (mass reduction at no additional costs or at a cost save). Next, all subsystems with a solution in Cost Group B were evaluated. If subsystems with a solution in Cost Group B had no existing Cost Group A solution, Cost Group B was automatically selected. If an existing A solution existed, an assessment was made to either stay at Cost Group A (no cost or cost savings with mass reduction) or move to the solution in Cost Group B, increasing the amount of mass reduction contribution at the defined cost increase. The decision to move from Cost Group A to Cost Group B was dependent on both the additional mass reduction and cost premium within the subsystem, as well as what other subsystems could offer in comparison relative to mass reduction and associated costs.

Upon completion of Cost Group B, a similar process was followed for evaluating the mass reduction solutions in Cost Group C relative to solutions in Cost Group B (or Cost Group A if no Cost Group B solutions existed). Subsequently mass reduction solutions in Cost Group D were compared to solutions in Cost Group C (or B and A), and solutions in Cost Group X were compared to solutions in Cost Group D (or, C, B and A). In the brake system example in **Figure 2.2-10**, the green boxed combinations were selected as the brake subsystem final solutions.

After a few iterations, a mass reduction of 287 kg (11.7% of baseline vehicle mass) was achieved at a Net Incremental Direct Manufacturing Cost (NIDMC) increase of $1017 ($3.54 per kg). When comparing the mass reduction against the baseline mass, for only those systems evaluated (i.e., not including body and frame vehicle systems), a 19.2% (287kg/1495kg) mass reduction was achieved. Based on preliminary results from the Body and Frame System assessments, and anticipated additional mass reduction as a result secondary mass-savings, the team felt confident that more than 20% vehicle mass reduction could be achieved with the selected subsystem solutions. The preliminary cost per kilogram estimate was also below the maximum project limit of $5.10/kilogram.

### 2.2.5 Step 5: Detailed Mass reduction Feasibility and Cost Analysis

Upon the selection of the optimized vehicle solution, and associated mass reduction ideas, additional engineering work was employed to verify the mass reduction ideas were feasible both from the design and manufacturing perspectives. The additional work was centered on expanding the supporting portfolio of information gathered on the mass reduction ideas using the same types of sources and methodology as used in the initial idea generation phase, including: researching existing industry published works in mass reduction, reference data from production benchmark databases, and speaking with material suppliers, automotive part suppliers, and alternative transportation industry suppliers. The research, the partnerships involved in the analysis, study assumptions, and calculations are all discussed in detail in **Section 4 Mass Reduction and Cost Analysis – Vehicle Systems White Papers.**

In some cases, the ideas originally selected for the detailed analysis did not work out. When this occurred, the team returned to the brainstorming template for similar value mass reduction ideas to try and ensure their system target mass reductions and costs were maintained. In other cases new alternative, better value ideas were discovered as part of the detailed analysis. When this occurred, the new, greater value mass reduction ideas replaced the original lessor value mass reduction ideas. From a mass reduction perspective, some of the vehicle systems went up in mass slightly, from the original mass reduction optimization model, while others came down by similar amounts.

Complete details on the costing assumptions, methodology and tools utilized in this analysis can be found in **Section 2.4**. Component specific manufacturing process and assumption details can be found in the applicable vehicle system whitepapers (**Section 4**). Since many of the detailed costing spreadsheet documents generated within this analysis are too large to be shown in their entirety, electronic copies can be accessed through EPA's electronic docket ID EPA-HQ-OAR-2010-0799 (**http://www.regulations.gov)**.

Upon completion of developing the final mass reduction and cost calculations for each vehicle system, the first two process steps (within Step 5) were repeated to account for secondary mass savings. Vehicle systems within the Powertrain, Chassis, and Trim Evaluation Group, which qualified from secondary mass-savings, included: engine, transmission, suspension, brake, exhaust and fuel systems. Established on the initial vehicle mass reduction results (results without secondary mass-savings), the team felt confident a minimum 20% vehicle mass reduction was achievable with secondary mass-savings. Proceeding with the 20% or 477 kg vehicle curb weight (CW) reduction assumption, systems with secondary mass-savings potential were re-evaluated for additional mass-savings via component downsizing.

Due to payload and towing requirements, the amount of effective downsizing was limited. The gross combined weight rating (GCWR) for the Silverado vehicle evaluated was 6804 kg (15,000 lbs.). The CW reduction in comparison to the GCWR is only 7% (477 kg/6,804 kg). Vehicle systems like the engine, transmission, brakes and suspension were all designed to perform based on the GCWR. Thus in the secondary mass-savings analysis, the impact of the 20% CW reduction, relative to the GCWR was considered. The final component downsizing percentages varied from system to system, details for each can be found in the respective vehicle system white paper (**Section 4**). Once the new component masses with the additional downsizing credits were established, cost models were updated to reflect the mass changes. For the Powertrain, Chassis, and Trim Evaluation Group, two set of cost models exist, one with and one without secondary mass-savings.

The final task in Step 5 was to develop a cost curve representing the average cost per kilogram of mass reduction in relationship to percent vehicle mass reduction. Cost curves with and without secondary mass-savings were developed. The process involved sorting component and assembly mass reduction ideas from best- to least-value. Starting at the best value mass reduction components, and working down the list, component's mass and costs were cumulatively summed to establish average cost per kilogram at increasing levels of vehicle mass reduction. In this first step only mass reduction without secondary mass-saving could be considered as secondary mass-savings were not consider at multiple percent vehicle mass reduction points. Extrapolating the $/kg of mass reduction out to 20.8% vehicle mass reduction (% mass reduction for the primary vehicle solution), a cost per kilogram comparison between mass reduction with and without secondary mass-savings was made. The additional benefit of secondary mass-savings at 20.8% vehicle mass reduction was then ratiometrically applied to other percent vehicle mass reduction points to create a secondary mass reduction cost curve. Additional details on cost curve development can be found in **Section 2.4.1.4**.

It addition to the cost curve, a cost curve with only the Powertrain, Chassis and Trim Evaluation Group Ideas was assembled as well as a Body Closure cost curve. A summary of all cost curves developed in the analysis can be found in Section 3.

## 2.3 Body and Frame Mass reduction Evaluation Group – Methodology Overview

The following section covers the methodology and tools used by EDAG to evaluate the body and frame vehicle systems. The general methodology for all vehicle systems shared similar steps as discussed in the Introduction section (i.e., teardown and fingerprinting the baseline vehicle, mass reduction idea generation, selection of vehicle mass reduction ideas, and detailed mass reduction feasibility and cost analysis), although considerably more analysis was conducted on the body and frame systems to ensure the generated mass reduction ideas would not degrade the primary safety, durability, or vehicle dynamics attributes of the vehicle.

### 2.3.1 Analysis Overview

The intent of the study is to demonstrate a light-weight pickup truck design that meets a generalized set of performance criteria, is cost-effective, and is achievable to manufacture in the 2020-2025 timeframe. To accomplish this objective, the team evaluated the structure and closures of a production Chevrolet 1500 Silverado Crew Cab using computer-aided engineering (CAE) tools. The typical CAE evaluation process followed is shown in **Figure 2.3-1**.

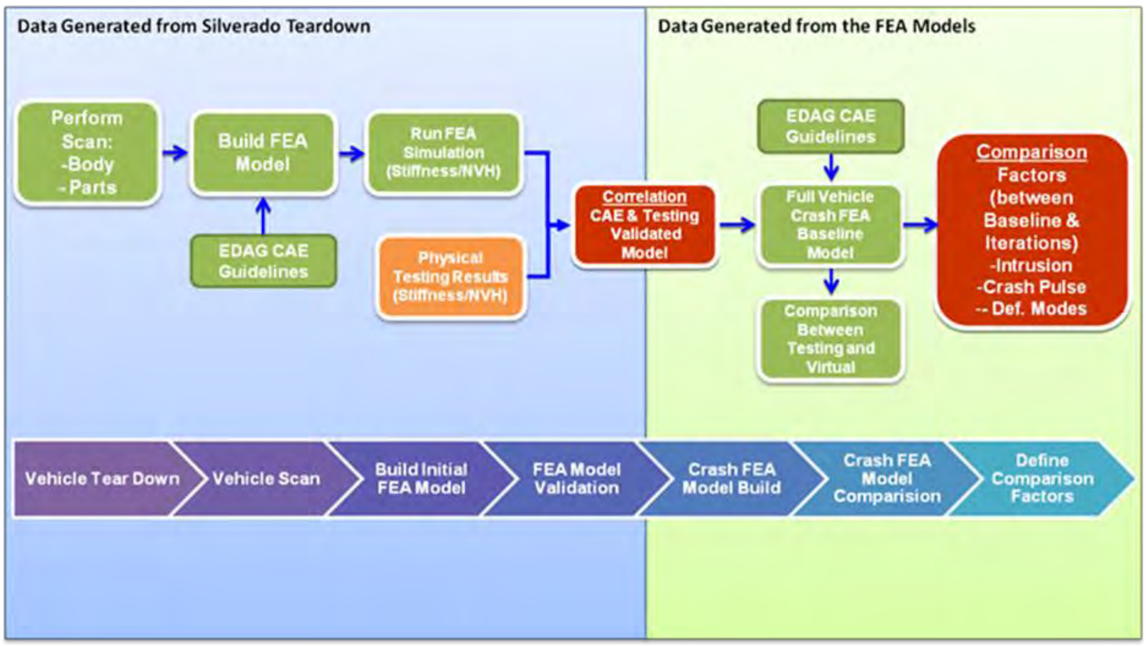



**Figure 2.3-1: CAE Evaluation Process and Components**

The baseline CAE model utilized was an updated version of the published NHTSA 2007 two-wheel drive Chevrolet 1500 Silverado Crew Cab finite element analysis (FEA) model. The baseline model was revised to include the new items found on the 2011 Chevrolet 1500 Silverado Crew Cab 4x4 teardown:

1. The frame, was updated to reflect the masses of the 2011 Chevrolet 1500 Silverado Crew Cab 4X4 frame;

2. The powertrain was updated with some of the major changes including:
    i. Updated engine/transmission mass and inertias
    ii. Added transmission and transfer case
    iii. Added front differential, front driveshaft and front half shafts
    iv. Updated rear driveshaft

v. Revised front brake calipers

3. The number and location of the vehicle welds were updated;
4. A new tow bar was added; and
5. The mass distribution was updated on the existing and added components consistent with the 2011 MY truck curb weight (CW) of 2,454kg (5,410lb) in the CAE model.

For the CAE analysis, only the structural performance was considered with the physical effects of dummies, seats, restraint systems or interior trim parts not included in the analysis. The modified CAE model was analytically tested with the results compared to actual noise, vibration, and harshness (NVH) and crash test results seen in the 2011 4x4 Chevrolet Silverado 1500 vehicles. The baseline model comparison included static NVH performance (<5% maximum difference) and regulatory safety crash load cases (visual comparison and quantitative comparison using intrusion, etc.). For the CAE analysis of crash safety scenarios, only the structural performance was considered (intrusion, g-force, etc.) with the physical effects of dummies, seats, restraint systems or interior trim parts not included in the analysis. Upon verifying that the model demonstrated acceptable quality based on established CAE practices, the model was deemed the baseline and then utilized as the reference for all further development of the light-weighting optimization processes.

Advanced, collaborative light-weighting design optimization was then carried out utilizing gauge, grade, and subsystem parameters in which the subsystem parameters were individually optimized, to create different weight reduction strategies.

The CAE evaluation cases include cost, structural stiffness (torsion and bending), regulatory crash requirements (high-speed, low-speed and roof crush), frame fatigue analysis, and vehicle dynamics performance. The detailed CAE evaluation of the body structure, cargo box, frame, and closures for the baseline and the light-weighting designs are presented in the following sub-sections.

### 2.3.2 Mass Reduction

The Silverado light-weighting project, for the Body and Frame Evaluation Group, was divided into the following phases and tasks.

- Phase 1: Data, Loadcases, and Baseline Generation
- Phase 2: Definition of comparison factors for Full Vehicle Analysis
- Phase 3: Modularization and System Analysis
- Phase 4: Full Vehicle Optimization

Based on EDAG best practices of CAE Evaluation process, various inputs, outputs, and tools used in each process task are provided in **Figure 2.3-2** and **Figure 2.3-3**.

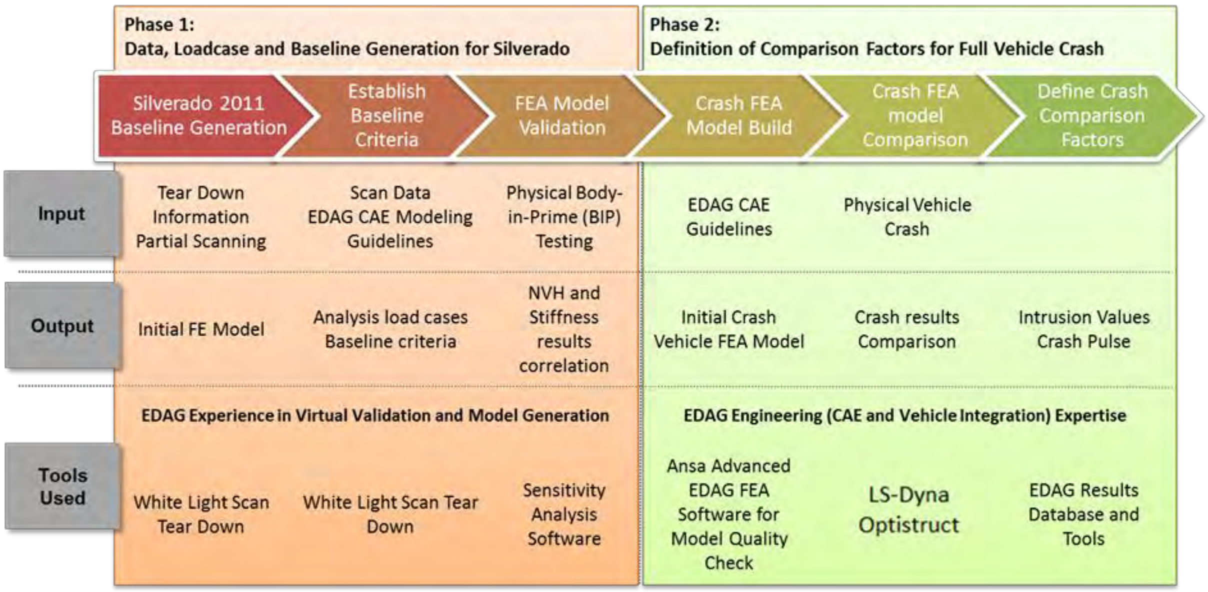



**Figure 2.3-2: Project Tasks Phase 1 and 2**

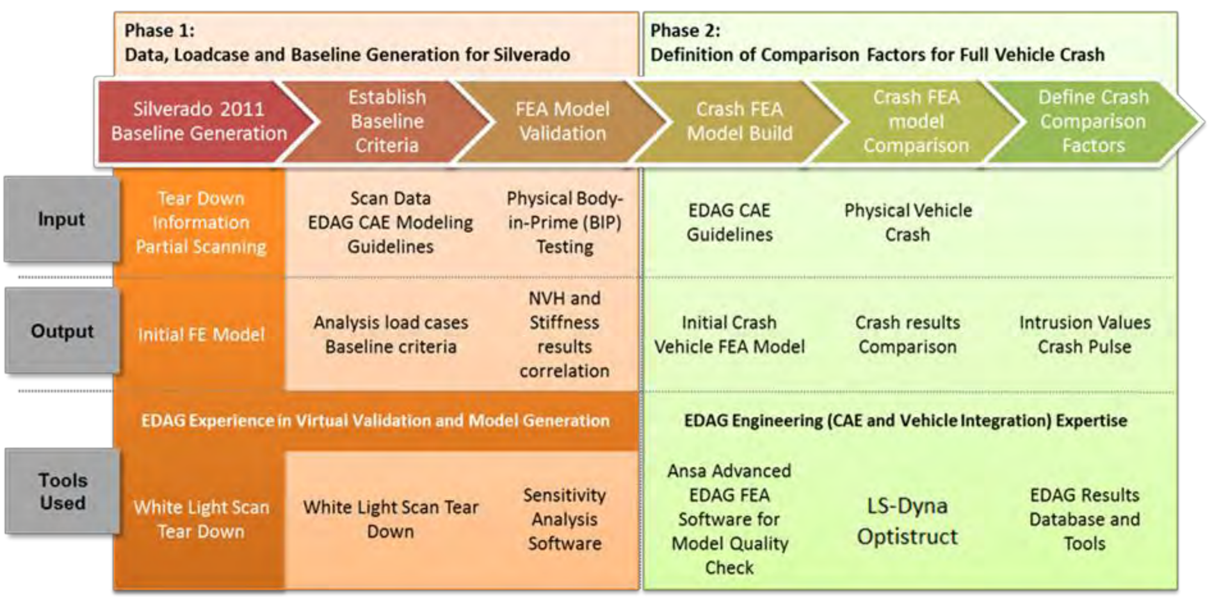



**Figure 2.3-3: Project Tasks Phase 3 and 4**

**Phase 1** included the collection of necessary engineering and analysis data such as vehicle Bill of Materials (BOM), subsystem and components properties, assembly scheme, part connections characteristics and material properties. From a CAE simulation perspective, most widely conducted CAE loadcases were decided from the subsystem to the full-vehicle level. Baseline models for each of the loadcases were also developed in this phase.

**Phase 2** was primarily intended for gathering the performance characteristics and comparison factors (performance criteria) for each loadcase. The target comparison key attributes in terms of subsystem and full-vehicle performance were established in Phase 2.

**Phase 3** and **Phase 4** were slotted for CAE-based weight-reduction optimization. An advanced collaborative optimization was carried out in these phases. The collaborative optimization included subsystem analyses and multi-disciplinary full-vehicle optimization by including NVH and crash safety loadcases in one optimization process. For this purpose, in Phase 3, finite element (FE) models were built by modularization techniques and subsystem analyses were carried out for subsystem-level weight reduction. In Phase 4 of the project, full-vehicle automated and interactive optimization cycles were executed. Phase 4 also included application of several weight-reduction strategies and EDAG best practices of unleashing maximum weight saving potentials.

Detailed overview of the general tasks of each phase is provided in the following sections.

#### 2.3.2.1 Phase 1: Data, Load Case and Baseline Generation for Silverado

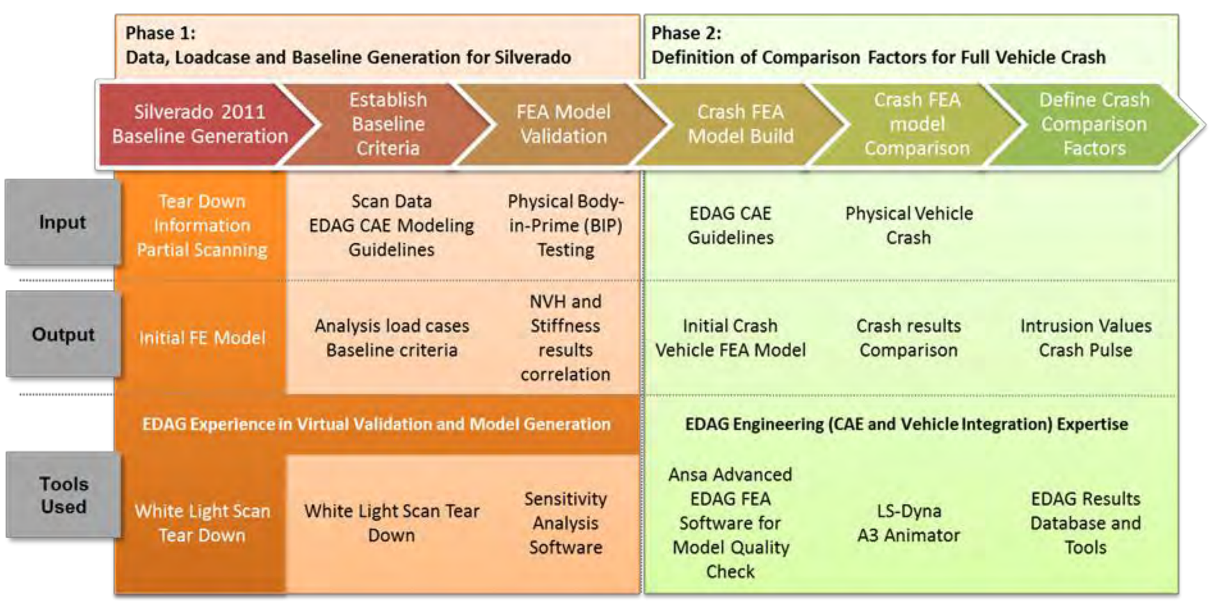



**Figure 2.3-4: Silverado 2011 Baseline Generation**

The process of baseline generation includes the following stages:

- Process-driven vehicle teardown to get the individual part and subsystem details including part weights.
- Scanning of the necessary parts and systems to obtain digital geometry and position data.
- Building initial Finite Element (FE) model.

##### 2.3.2.1.1 Vehicle Teardown

A 2011 Silverado was purchased and completely disassembled by skilled body technicians. GM body repair manuals were used to aid in the disassembly of vehicle. Part details and metadata crucial for building the CAE model (such as part weight, material, and thickness) were obtained and recorded in an assembly hierarchy (**Figure 2.3-5**).

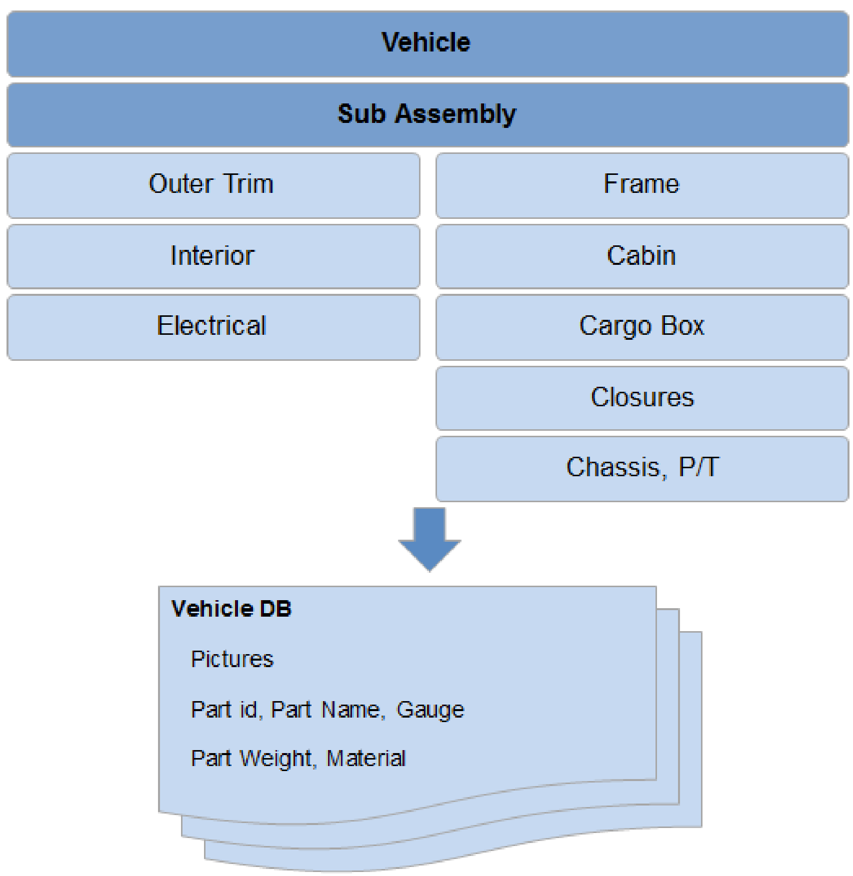



**Figure 2.3-5: Vehicle Teardown Process**

Photos of the disassembled body parts used in the CAE model are shown in **Appendix Section 7.2.1**.

EDAG's project scope included determining the baseline vehicle weights through measurement or calculation. Upon obtaining these weights, including the overall body weight, major subassembly weights, and key component weights, they were then charted (**Table 2.3-1**). This information was used as the baseline weights in the subsequent CAE evaluation process (**Figure 2.3-6**).

**Table 2.3-1: Mass of Baseline Body and Frame Components and Assemblies**

| 2011 Silverado Model | |
|---|---|
| System | Baseline Model Mass (Kg) |
| Body and Frame Structure Subsystems | |
| Box Assembly Pick-Up | 108.3 |
| Frame Assembly | 242.0 |
| Cabin | 207.2 |
| Panel Fender Outer LH | 14.9 |
| Panel Fender Outer RH | 14.0 |
| Radiator Structure | 12.9 |
| IP XMbr Beam Assembly | 12.1 |
| Extra Cabin - Radiator Support | 12.1 |
| **Sub-Total** | **623.5** |
| Body Closure Subsystems | |
| Bumper Front | 28.5 |
| Bumper Rear | 19.9 |
| Hood Assembly without Hinges | 22.7 |
| Door Assembly Front LH | 29.0 |
| Door Assembly Front RH | 28.9 |
| Door Assembly Rear LH | 22.0 |
| Door Assembly Rear RH | 22.2 |
| Cargo Box Gate | 18.8 |
| **Sub-Total** | **192.0** |
| **Total Mass** | **815.5** |

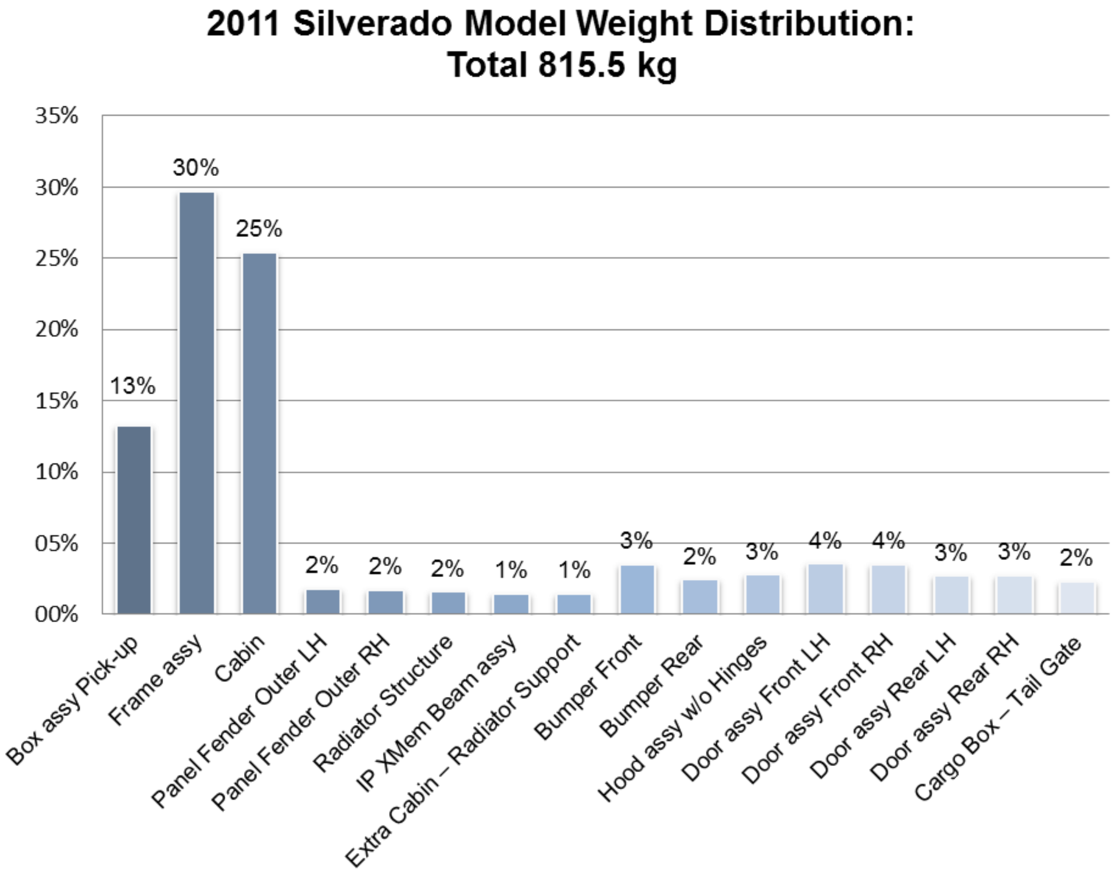



**Figure 2.3-6: Baseline Vehicle Component Distribution**

#### 2.3.2.1.2 Vehicle Scanning

For the purpose of building the baseline FE model, the pre-evaluated crash CAE model of a 2007 Silverado (donor model) was gathered from National Crash Analysis Center (NCAC), George Washington University.

The 2007 Silverado was compared and revised with the 2011 Silverado assembly information obtained from the teardown data. The areas updated from the 2007 model are detailed in **Appendix Section 7.2.8**.

The geometry of each of the updated component parts was obtained by using White Light Scanning (WLS) techniques and stored in stereo lithography (STL) format. **Figure 2.3-7** shows the methodology used in identifying the parts for scanning. In addition to part geometry, the part connection (such as location and type – e.g., spot weld, seam weld, laser weld), dimensions (e.g., weld diameter, weld length), and characteristics (e.g., bushing) were also captured during the scanning process.

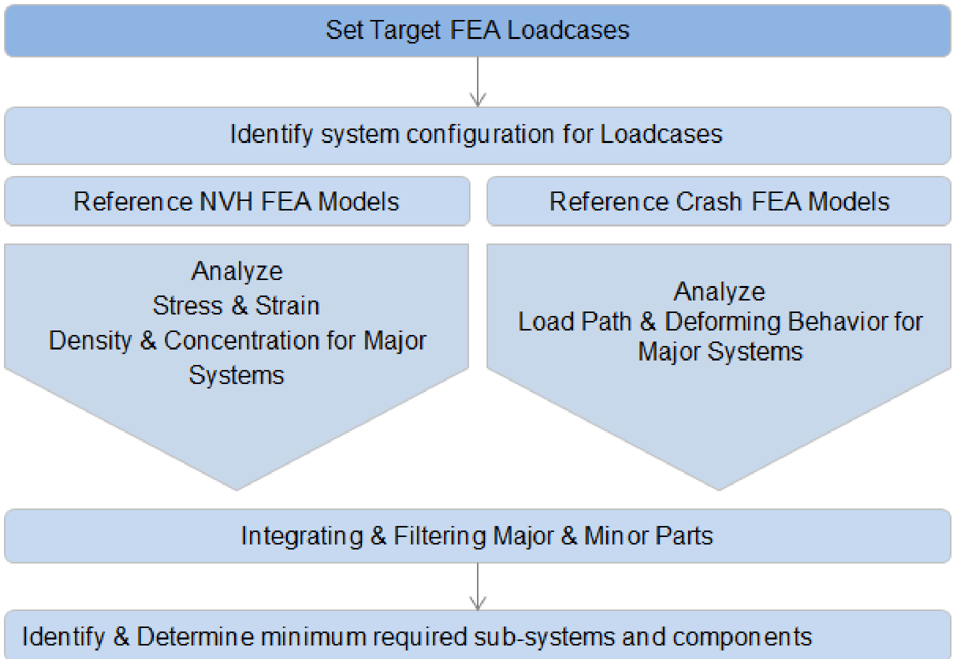



**Figure 2.3-7: White Light Scanning Part Identification Methodology**

Sample images of raw STL data obtained by WLS of the body structure parts are shown in **Appendix Figure 7.2-1**.

2.3.2.1.3 Baseline FE Model

A FE model of the scanned parts was constructed using finite element mesh (from geometry data), part-to-part connection data, and part characteristics (material data). The geometry and connection data were obtained from the scanning process.

2.3.2.1.4 FE Modeling

A commercially available FE meshing tool (ANSA)[7] was used to generate FE mesh from the raw STL geometry data obtained from WLS. A schematic of the process of meshing from raw STL data is shown in **Figure 2.3-8**.

7 ANSA User's Manual 2012

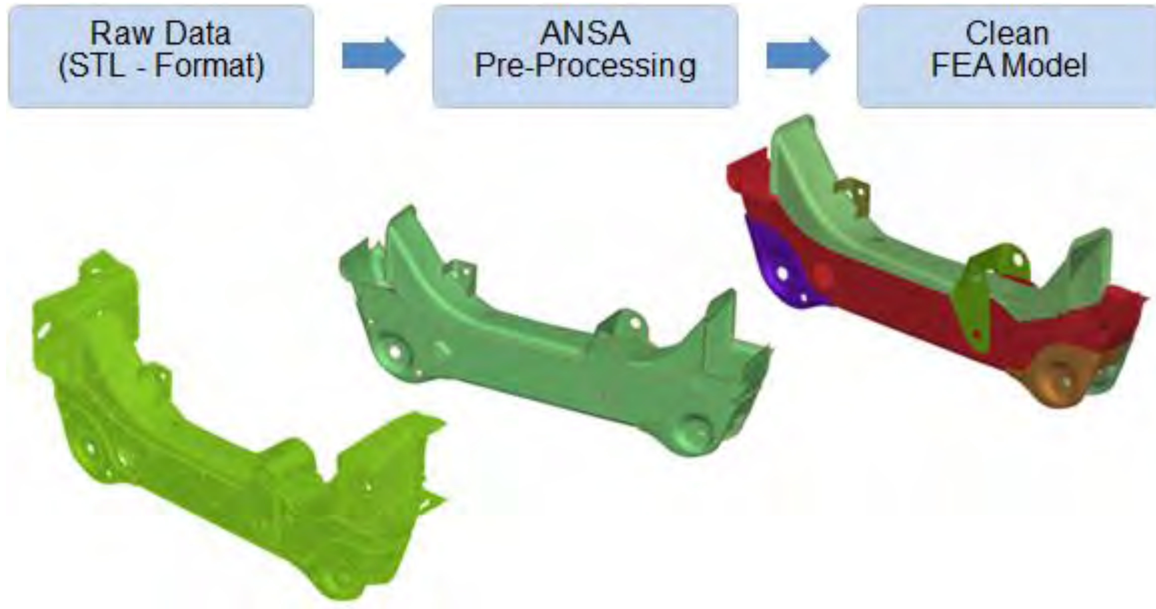



**Figure 2.3-8: Mesh Generation from STL Raw Data**
*(Source: EDAG, Inc.)*

The raw STL data (e.g., front cross member) was imported into the meshing tool. The geometry was then cleaned and meshed as per EDAG meshing quality standards. The meshed parts were assembled using the connection scheme in the vehicle, which was captured and documented as part of the scanning activity. EDAG CAE guidelines[8, 9] were followed in building the complete frame assembly hierarchy. **Figure 2.3-9** shows the 2011 Silverado frame assembly FE model developed from the above teardown-scanning process.

8 EDAG CAE Crash and Safety Modeling Guidelines Revision 2.0 Nov. 2010

9 EDAG CAE NVH Modeling Guidelines Revision 2.0 Nov. 2010

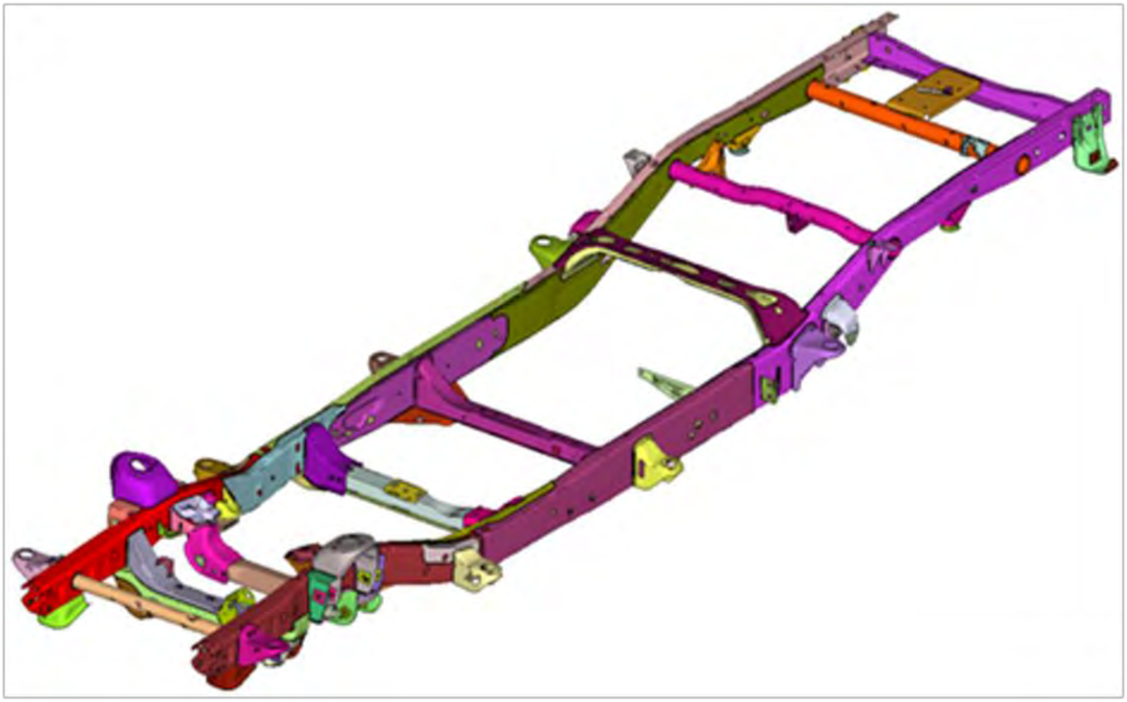


**Figure 2.3-9: FE Model of 2011 Silverado Frame Assembly**
**(Individual parts are shown in different colors)**
*(Source: EDAG, Inc.)*

The frame assembly was then integrated into the 2007 Silverado FE model. The full vehicle model was carefully examined for the remaining subsystems and components compatibility as per 2011 Silverado design space, materials, and connections. **Figure 2.3-10** shows the completely assembled FE model of the 2011 Silverado.

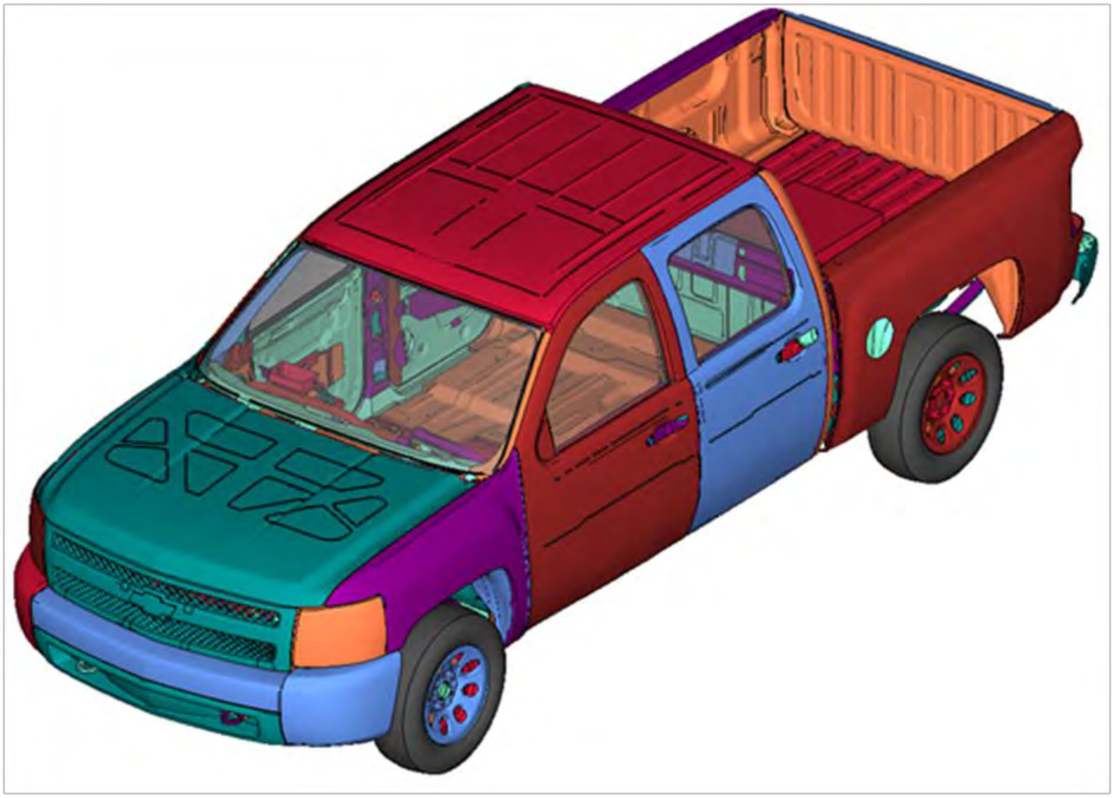


**Figure 2.3-10: FE Model of 2011 Silverado**
**(Assemblies are shown in different colors)**
*(Source: EDAG, Inc.)*

The FEA model was built using subsystem modules methodology. This methodology allows for subsystem model parameterization and independent analysis, which will be used during the optimization process. The modules consisted of the following assemblies:

- Body-in-white
- Frame
- Cabin
- Cargo box
- Front and rear bumpers
- Front and rear doors
- Hood
- Tailgate
- Chassis components
- Engine and other powertrain components

The gauge (thickness) and material data for each part were accordingly incorporated into the model. Parts that were not represented as geometry were added in the model as mass elements with weight and inertia characteristics.

**Figure 2.3-11** shows the main subsystems modules of 2011 Silverado model.

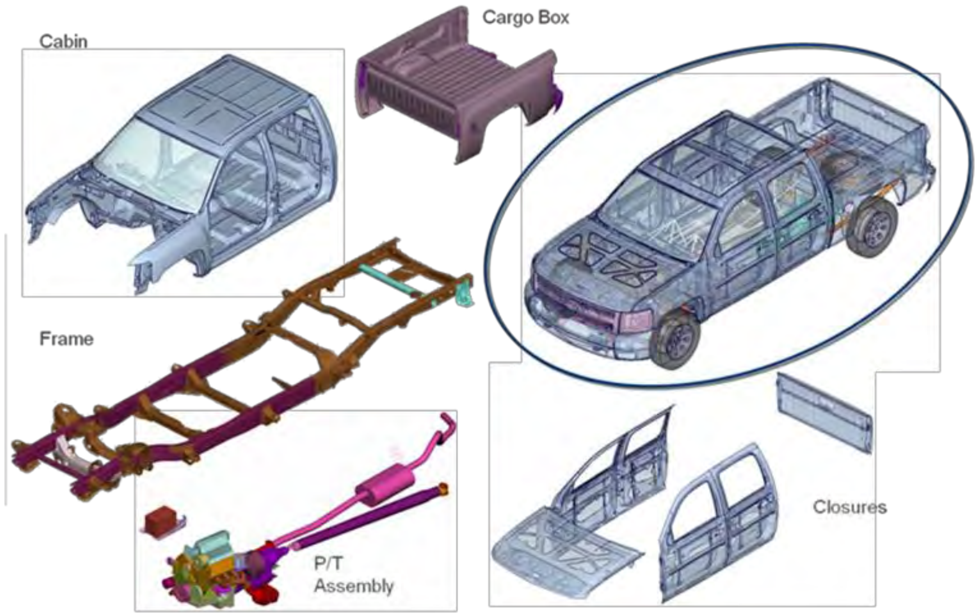



**Figure 2.3-11: 2011 Silverado Baseline Subsystems**
*(Source: EDAG, Inc.)*

2.3.2.1.5 <u>FE Materials Selection</u>

Materials are assigned to the structural parts based on the existing NCAC LS-DYNA model or the new data obtained from the 2011 Silverado scan. Only the laminated glass included failure modes since it was required for roof crush and side pole crash testing. No other damage or failure modes were included..

Details of the material models used in this study are shown in **Appendix Section 7.2.3**.

2.3.2.1.6 <u>Establish Baseline Criteria</u>

The baseline model was established by comparing a number of criteria to the actual vehicle (**Figure 2.3-12**). Analysis of weight comparison, NVH, Crash and Safety, Durability, Bumper Impact Performance, and Vehicle Dynamics were studied. The results of the weight comparison are included in the results section of this section. The Bumper Impact and Vehicle Dynamics analyses and results are presented in the results for the light-weighted CAE design.

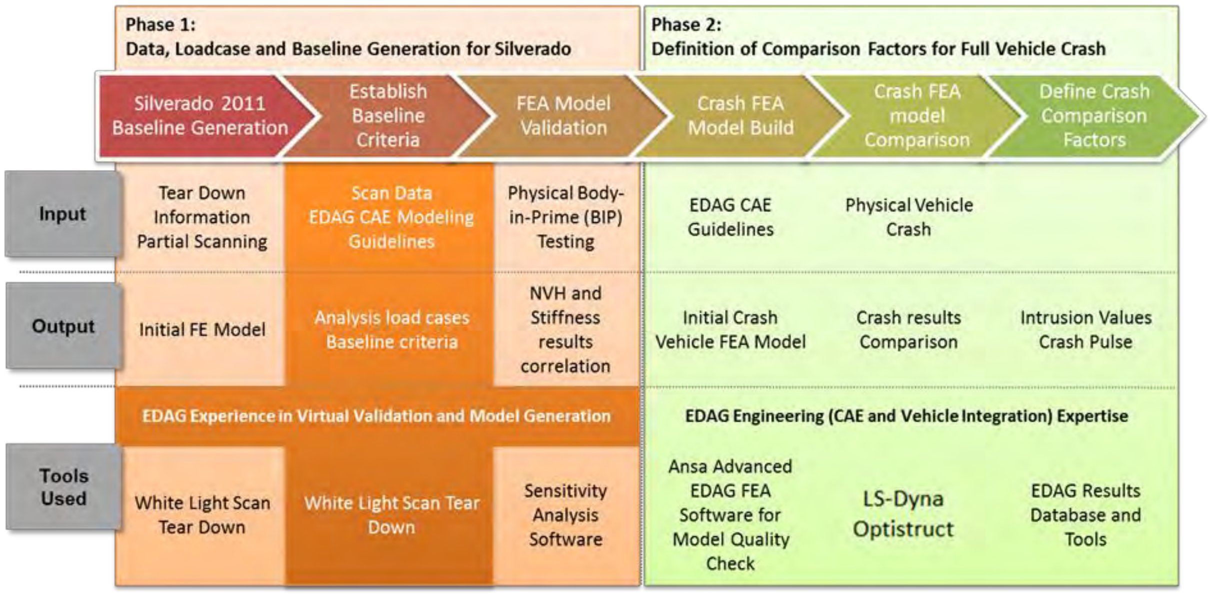



**Figure 2.3-12: Establish Baseline Criteria**

The process of building the baseline finite element analysis (FEA) models from the initial FE model involves first gathering all applicable loadcases which can be performed in virtual CAE analysis and their corresponding simulation output measures. The loadcases were identified from each test domain:

- NVH
- Crash and Safety
- Durability
- Vehicle Dynamics

This section provides a comprehensive list of the loadcases performed for subsystems and full vehicle.

#### *2.3.2.1.6.1 Loadcases*

The following loadcases (**Table 2.3-2**) of different analysis areas (disciplines) are considered in this study.

**Table 2.3-2: CAE Loadcases Overview**

| Discipline | System | Loadcase | Measures | No. |
|---|---|---|---|---|
| NVH | Frame | Static Bending | Global bending stiffness | 1 |
| | | Static Torsion | Global torsion stiffness | 2 |
| | Cabin | Static Bending | Global bending stiffness | 3 |
| | | Static Torsion | Global torsion stiffness | 4 |
| | Cargo Box | Static Bending | Global bending stiffness | 5 |
| | | Static Torsion | Global torsion stiffness | 6 |
| | Body On Frame | Static Bending | Global bending stiffness | 7 |
| | | Static Torsion | Global torsion stiffness | 8 |
| Crash / Safety | Full Vehicle | FMVSS 208—35 mph flat frontal crash (US NCAP) | Pulse<br>Crush<br>Time-to-zero velocity<br>Dash intrusions | 9 |
| | | IIHS—40 mph ODB frontal crash | Pulse<br>Crush<br>Time-to-zero velocity<br>Dash intrusions | 10 |
| | | FMVSS 214—38.5 mph MDB side impact (US SINCAP) | B-Pillar velocity<br>Side structure intrusions | 11 |
| | | IIHS—31.0 mph MDB side impact | B-Pillar velocity<br>B-Pillar intrusions<br>Survival space<br>Exterior crush | 12 |
| | | FMVSS 214—20 mph 5th percentile pole side impact | B-Pillar velocity<br>B-Pillar intrusions<br>Structure intrusions | 13 |
| | | FMVSS 301—50 mph MDB rear impact | Under structural zone deformation<br>Door operability<br>Fuel tank damage | 14 |
| | | FMVSS 261a—Roof crush | Roof strength to weight ratio | 15 |
| | | FMVSS 581—Bumper impact | Front end deformation | 16 |

**Table 2.3-2 continued next page**

**Table 2.3-2 continued**

| Discipline | System | Loadcase | Measures | No. |
|---|---|---|---|---|
| Durability | Frame | Fatigue | Components Life cycle | 17 |
| | Doors | Frame rigidity | Stiffness | 18 |
| | | Beltline compression | Stiffness | 19 |
| | | Beltline expansion | Stiffness | 20 |
| | | Torsion | Twist stiffness | 21 |
| | | Sag | Vertical deformation | 22 |
| | | Oil canning | Outer Panel deformation | 23 |
| | Hood | Bending | Stiffness | 24 |
| | | Torsion | Twist stiffness | 25 |
| | | Oil canning | Outer Panel deformation | 26 |
| | Tail gate | Torsion | Twist stiffness | 27 |
| | | Oil canning | Outer Panel deformation | 28 |
| Vehicle Dynamics | Full Vehicle | Constant Radius | Understeer Gradient<br>Cornering Compliance<br>Roll Gradient | 29 |
| | | J-Turn | Tire Load | 30 |
| | | Frequency Response | Steering Response Gain<br>Steering Response Phase lag | 31 |
| | | Static Stability Factor (SSF) | Track width/(2 x CG height) | 32 |

2.3.2.1.7 FEA Model Validation—Baseline NVH Model

The initial (baseline) models were validated as a valid engineering tool by (**Figure 2.3-13**):

- Building the models using rigorous structured quality processes.
- Associating actual test results with simulation results for selected loadcases.

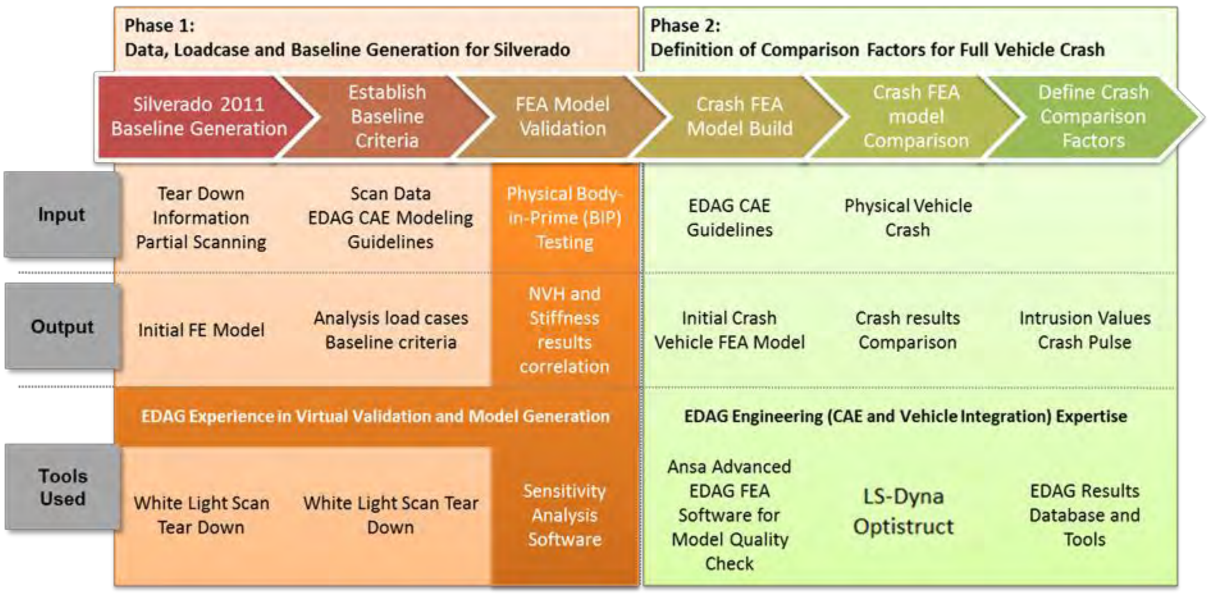



**Figure 2.3-13: FEA Model Validation: Baseline NVH and Crash Models**

The following subset of the loadcases was used to validate the FEA models. The model was analyzed in parts (frame, cabin, and box) as well as all together.

**NVH Loadcases (tests conducted at Ford Motor Company test labs)**

- Frame - Static Bending and Static Torsion
- Cabin - Static Bending and Static Torsion
- Body On Frame - Static Bending and Static Torsion

**Crashworthiness Loadcases (utilizing NHTSA test data) Full Vehicle**

- FMVSS 208—35 mph flat frontal crash
- FMVSS 214—38.5 mph MDB side impact
- FMVSS 214—20 mph $5^{th}$ Percentile pole side impact

See **Table 2.3-3** for a summary of the CAE Model parts and elements for the baseline and light weight development which includes the following:

**Table 2.3-3: Model Parts and Elements Summary**

| Vehicle Part | Parts | # Shell and Solid Elements | FE Weld elements | Model (2007/2011) |
|---|---|---|---|---|
| Frame | 100 | 287787 shell | Seam welds | 2011 |
| Cabin | 138 | 279700 shell<br>4458 solid | Physical spot welds | 2007/2011 with updated weld locals |
| Box | 32 | 113254 | Physical spot welds | 2007/2011 same |
| Full Vehicle** | 384 | 756554 shell and solid | Spot welds, seam welds, bolts and bushings | 2007/2011 |
| **includes extra parts and (elements) for holding the different vehicle parts together | | | | |

### *2.3.2.1.7.1 FEA Model Validation Process*

The validation of the FEA model for NVH was carried out in two different steps based on EDAG expertise and engineering knowledge. A summary of the model validation and EDAG CAE baseline model creation is illustrated in **Figure 2.3-14**.

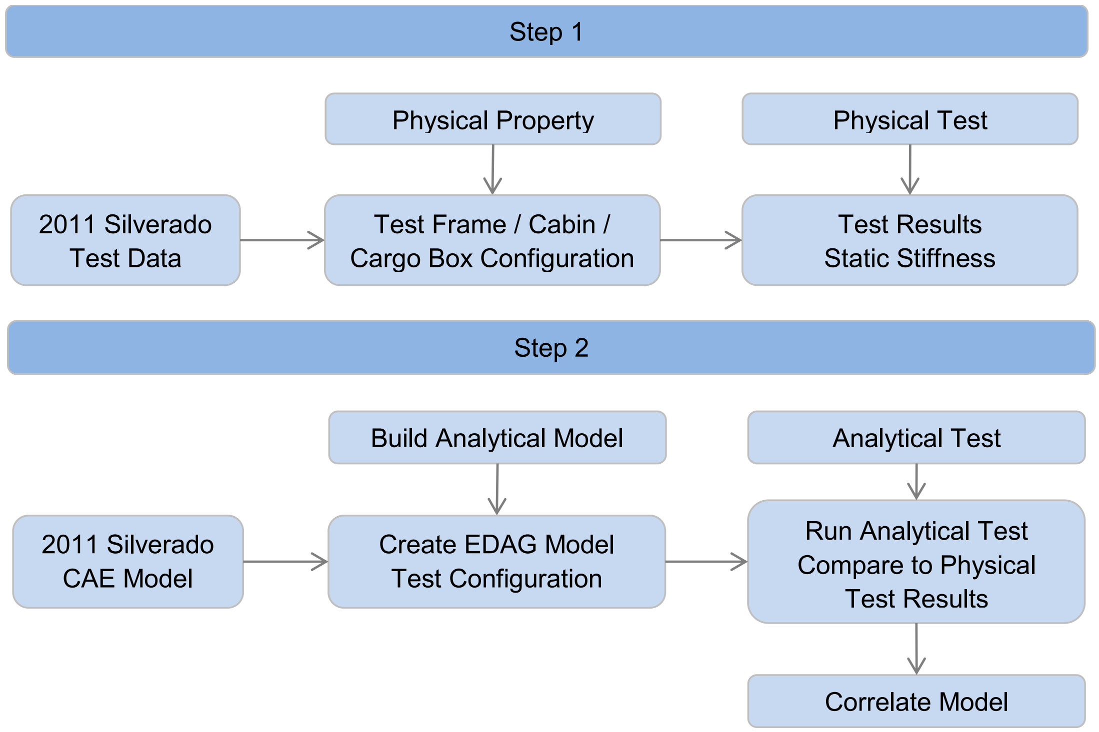



**Figure 2.3-14: Process Flow to Build Baseline Model**

**Step I**: NVH test setup and collect NVH test results (Test on Actual Vehicle, data purchased from Ford Motor Company).

**Step II**: EDAG CAE baseline model construction and correlation of NVH model. (Baseline model is a 2007 2WD with 2011 updates, 4WD weights, and the major 4x4 powertrain components added.)

The following NVH static loadcases were used to validate the initial FE models of frame and cabin configurations:

- Frame static bending and torsional stiffness
- Cabin static bending and torsional stiffness
- Whole Vehicle bending and torsional stiffness

The cargo box and closure models are as per the 2007 NHTSA model with no further validation performed.

#### *2.3.2.1.7.2 Frame*

**Model Statistics**

The frame model consisted of a front-, mid-, and rear-rail assemblies, cross members, shock towers, and body mount brackets. The FEA model of the entire frame assembly contained 100 parts made up of 287,787 shell elements. The parts were connected by means of FE weld elements representing seam welds.

The necessary loadcase-specific boundary conditions were incorporated into the corresponding model using commercially available pre- and post-processing tools and analyzed using Altair's Optistruct solver. The model setup in terms of boundary and load conditions is explained in detail for each of the NVH load cases. **Figure 2.3-15** shows the frame model before incorporating the boundary and load conditions.

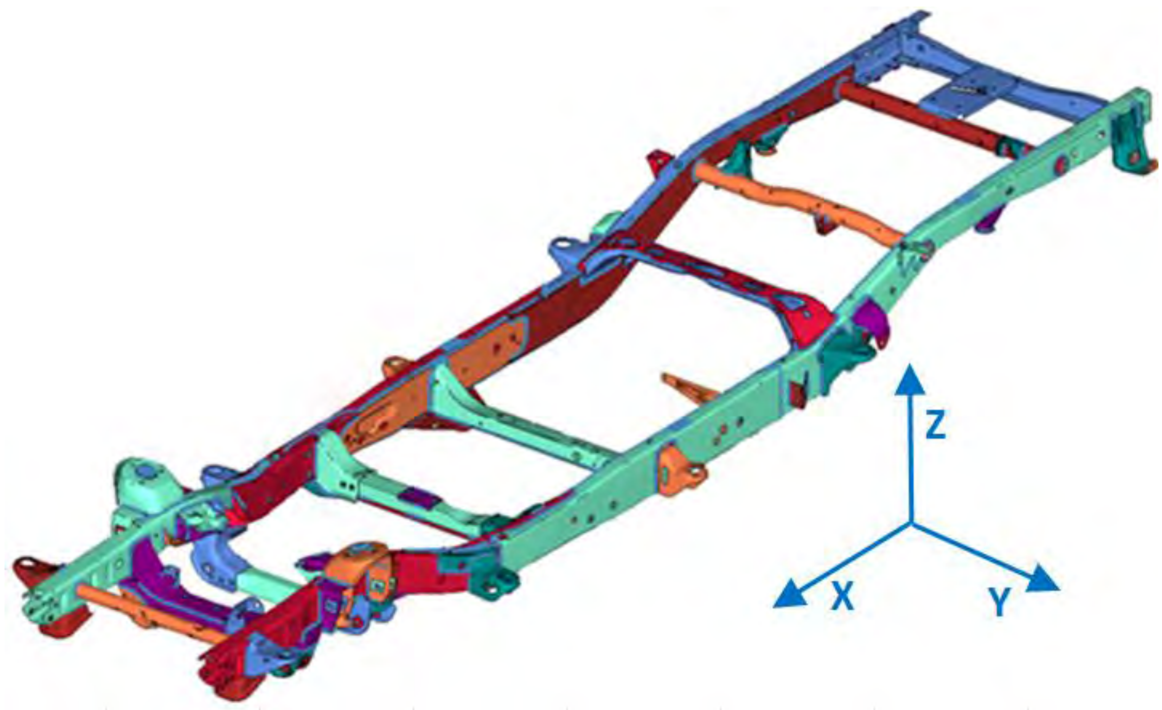



**Figure 2.3-15: Frame NVH Model**
*(Source: EDAG, Inc.)*

**Static Bending Stiffness**

In the bending stiffness model, the frame was constrained and loaded as shown in **Figure 2.3-16**. The rear-left shock tower was constrained in the x-, y-, and z-axes; the rear-right shock tower was constrained in the x- and z-axes; the front left shock tower was constrained in they and z-axes; and the front right shock tower was constrained in the z-axis. A bending load of 2,224N was applied at the center of the mid rail (midway between front and rear seats).

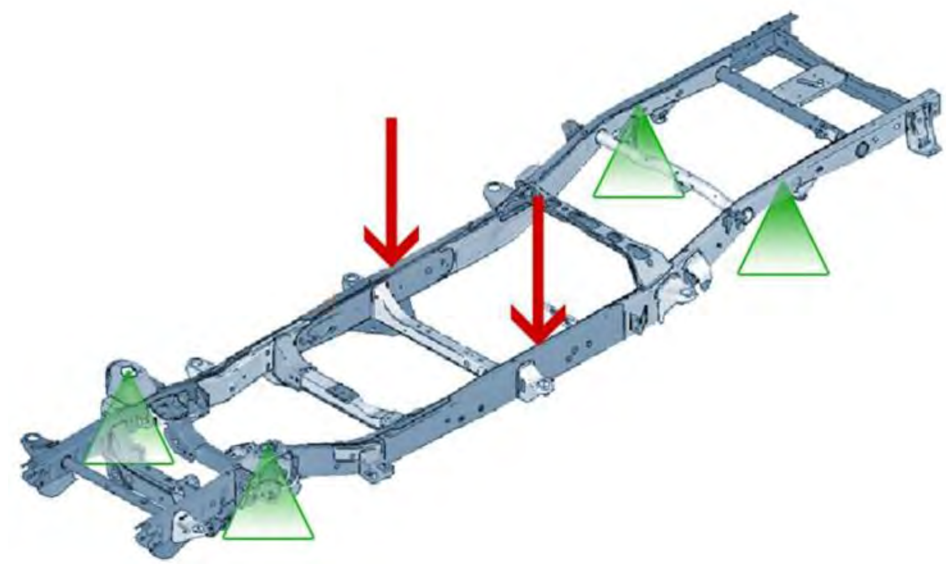


**Figure 2.3-16: Loads and Constraints on Frame NVH Model for Bending Stiffness**
*(Source: EDAG, Inc.)*

The calculation of bending stiffness was calculated using the Z-displacement on the mid rail under the defined load, and noting the maximum displacement on each measured location.

$$Bending\ Stiffness = \frac{Total\ Force}{Maximum\ Displacement}$$

### Static Torsion Stiffness

The torsion stiffness frame model was constrained and loaded, as shown in **Figure 2.3-17**. The rear-left shock tower was constrained in the x-, y-, and z-axes; the rear-right shock tower was constrained in the x- and z-axes. Additionally, the center of the front bumper was constrained in the z-direction. Vertical loads of 1,200N were applied in opposite directions on the left- and right-front shock towers. Torsional stiffness was calculated from the applied load and deflection.

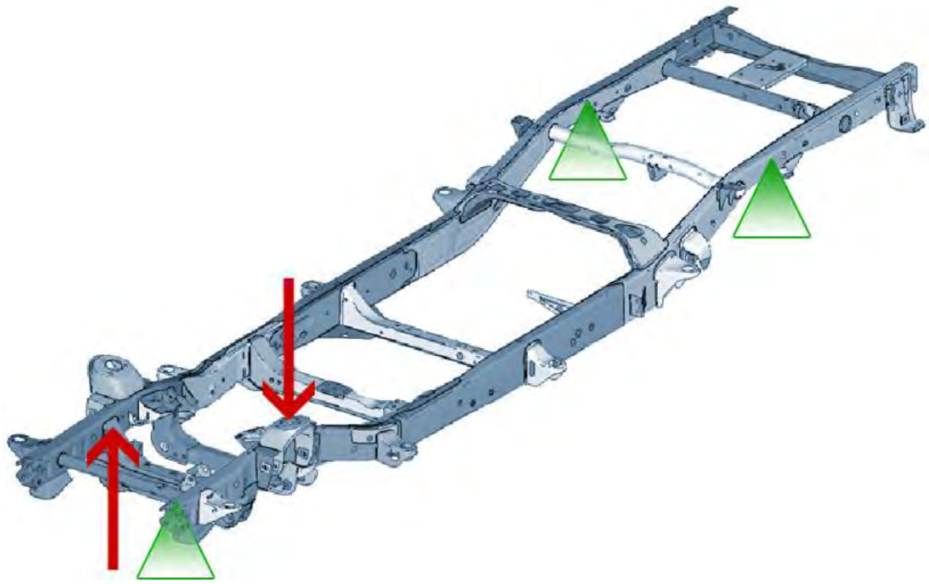


**Figure 2.3-17: Load and Constraints on Frame NVH Model for Torsional Stiffness**
*(Source: EDAG, Inc.)*

The calculation of torsion stiffness was done using the angular displacement of the frame under certain load. The average of the Z-displacement (Z) at the shock tower was calculated, and then the distance between the shock towers (D) was measured. The angular displacement (w) was calculated as ATAN (Z/D).

Torsion Stiffness=Total Force*Angular Displacement

**Step 1: NVH Test Setup**

A 2011Silverado frame was arranged with the necessary test equipment for static bending and static torsion measurements. The testing was conducted at the Ford Motor Company test labs.

**Static Bending Stiffness Test Setup**

For testing purposes, the frame was instrumented with the necessary deformation measuring gages at the selected locations. The bending test setup is shown in **Image 2.3-1**. The deformations at different locations were measured by applying a 2,224N force at the left and right rocker sections of the front door opening.


**Image 2.3-1: Bending Stiffness Testing Setup at the Laboratory**
*(Source: FEV, Inc.)*

With respect to the 2011 Silverado frame assembly, the CAE model was created as an exact replica of the test setup in order to achieve the test correlation. **Figure 2.3-16** and **Figure 2.3-18** show the static bending CAE setup equivalent to the test vehicle.

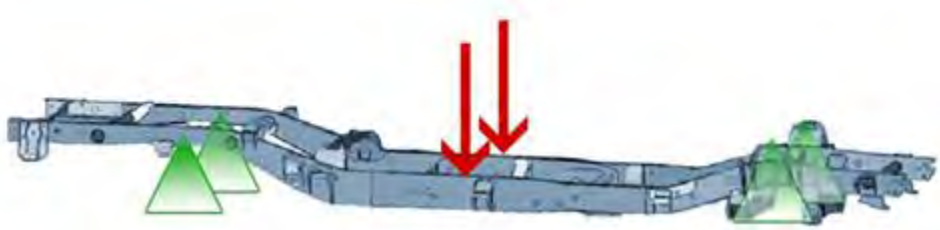


**Figure 2.3-18: Bending Stiffness CAE Setup**
*(Source: EDAG, Inc.)*

**Static Torsion Stiffness Test Setup**

Similarly, the vehicle was instrumented for measurement of torsion stiffness characteristics as shown in **Image 2.3-2**.

**Image 2.3-2: Torsion Stiffness Testing Setup**
*(Source: FEV, Inc.)*

The necessary deformations were measured at different test locations by applying 1,200N and -1,200N on the left and right shock towers respectively. The CAE model was created by incorporating the same boundary and loading conditions as seen in the physical test setup. **Figure 2.3-19** shows the equivalent CAE model for the torsion stiffness test setup.

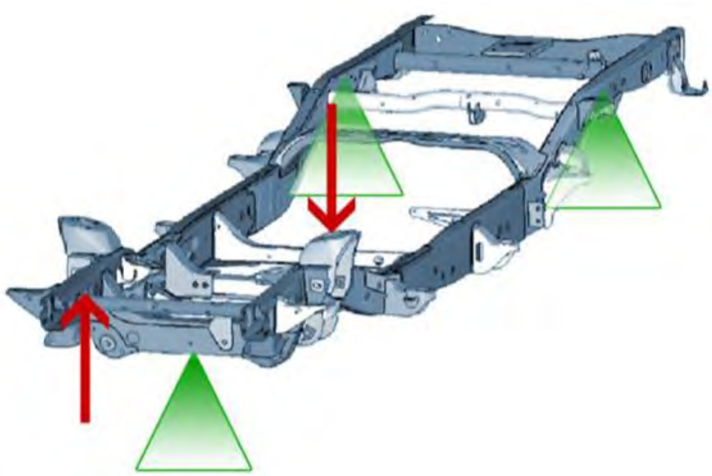


**Figure 2.3-19: Torsion Stiffness CAE Setup**
*(Source: EDAG, Inc.)*

**<u>Step 2: EDAG CAE Baseline Model</u>**

**Frame Correlation Summary**

The Baseline NVH Frame model was verified by the physical weight and material data. The test variants considered for the correlation were weight, global bending stiffness, and global torsion stiffness.

Altair's Optistruct solver was used to analyze the NVH loadcases. The results of the NVH simulations were studied with respect to the test results. The correlations of the CAE test results of the frame NVH load cases can be found in **Section 4.18**.

The same NVH baseline model was integrated accordingly to create the crash safety and durability baseline models. The model setup and loadcase creations for these disciplines are explained later in this report.

###### *2.3.2.1.7.3 Cabin Correlation*

**Model Statistics**

The cabin only NVH model consisted of all cabin parts welded, including radiator support and glass. The meshed model of the Silverado baseline cabin model contained 138 parts made up of 279,700 shell elements and 4,458 solid elements.

The necessary loadcase specific boundary conditions were incorporated into the corresponding model using commercially available pre- and post-processing tools and then analyzed using Altair's Optistruct solver. The model setup in terms of boundary and load conditions is explained in detail for each of the NVH load cases. **Figure 2.3-20** shows the NVH model before incorporating the boundary and load conditions.

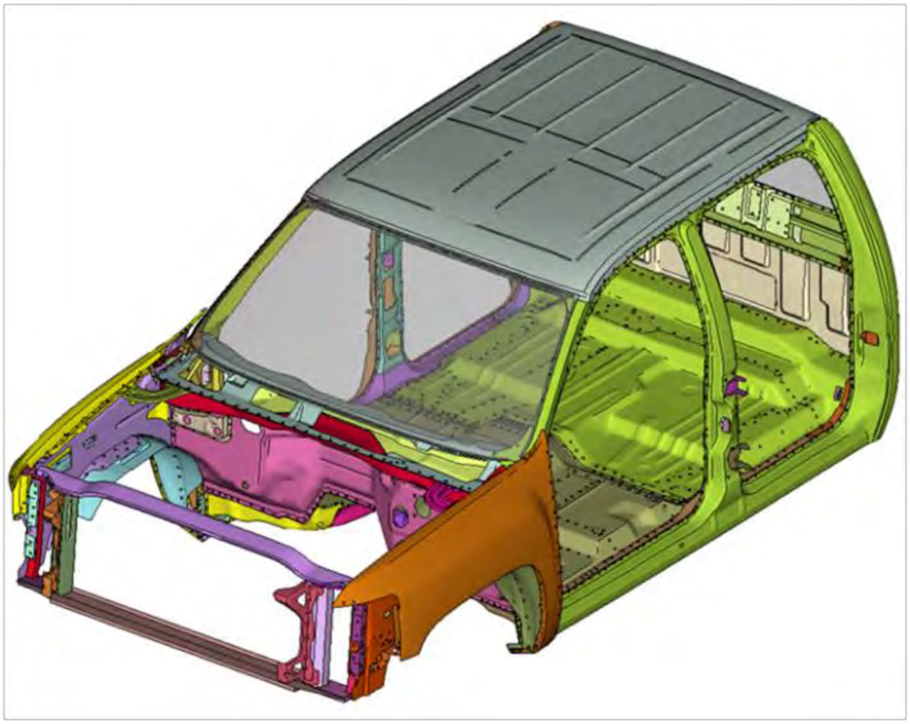


**Figure 2.3-20: Cabin NVH Model**
*(Source: EDAG, Inc.)*

### Static Bending Stiffness

In the bending stiffness model, the cabin was constrained and loaded as shown in **Figure 2.3-21**. The rear-left body mount was constrained in the x-, y-, and z-axes; the rear-right body mount was constrained in the x- and z-axes; the front left body mount was constrained in the y- and z-axes; and the front right body mount was constrained in the z-axis. A bending load of 2,224N was applied on top of the rocker/sill as shown in Figure 2.3-21.

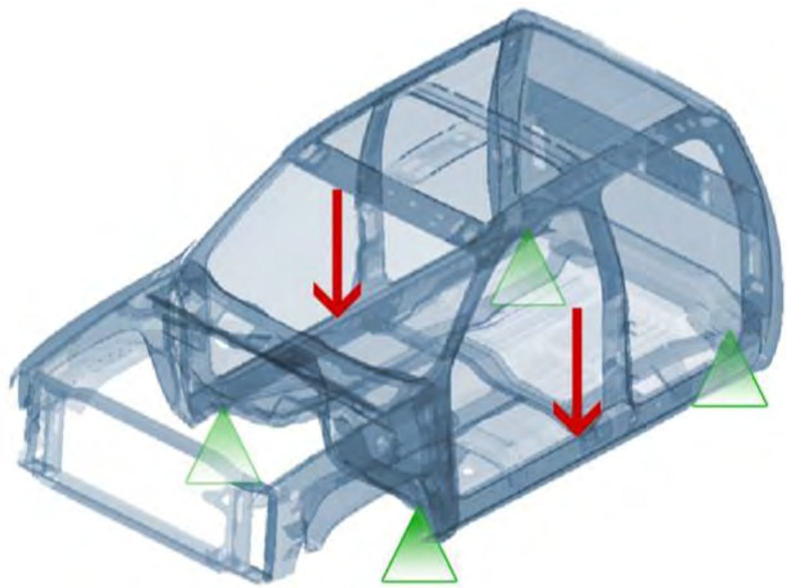


**Figure 2.3-21: Loads and Constraints on Cabin NVH Model for Bending Stiffness**
*(Source: EDAG, Inc.)*

The calculation of bending stiffness was done by measuring the Z-displacement on the rocker, noting the maximum displacement on each measured location.

$$Bending\ Stiffness = \frac{Total\ Force}{Maximum\ Displacement}$$

### Static Torsion Stiffness

The torsion stiffness cabin model was constrained and loaded, as shown in **Figure 2.3-22**. The rear-left mount was constrained in the x-, y-, and z-axes; the rear-right mount was constrained in the x- and z-axes. Additionally, the center of the front dash board is constrained in the z-direction. Vertical loads of 1,200N were applied in opposite directions on the left and right-front mounts. Torsional stiffness was calculated from the applied load and deflection.

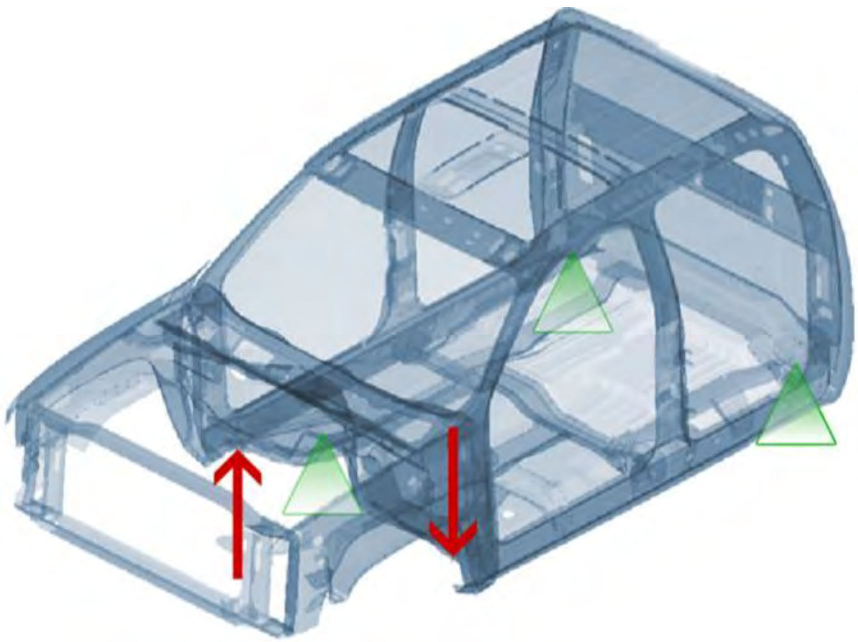


**Figure 2.3-22: Load and Constraints on Cabin NVH Model for Torsional Stiffness**
*(Source: EDAG, Inc.)*

The calculation of torsion stiffness was done by using the angular displacement of the frame generated when applying certain load. The average of the Z-displacement (Z) at the front body mounts was calculated, and then the distance between the front body mounts (D) was measured. The angular displacement (w) was calculated as ATAN (Z/D).

$$Torsion\ Stiffness = Total\ Force * Angular\ Displacement$$

**Step 1: NVH Test Setup**

A 2011 Silverado cabin was setup with the necessary test equipment for static bending and static torsion measurements. The testing was conducted at the Ford Motor Company NVH labs.

**Static Bending Stiffness Test Setup**

For testing purposes, the cabin was instrumented with the necessary deformation measuring gages at the selected locations. The bending test setup of cabin is shown in **Image 2.3-3**. The deformations at different locations were measured by applying a 2,224N force at the left and right rocker sections of the front door opening.

**Image 2.3-3: Bending Stiffness Testing Setup**
*(Source: FEV, Inc.)*

With respect to the 2011 Silverado cabin assembly, the CAE model was created as an exact replica of the test setup in order to achieve the test correlation. **Figure 2.3-21** and **Figure 2.3-23** show the static bending CAE setup equivalent to the test vehicle.

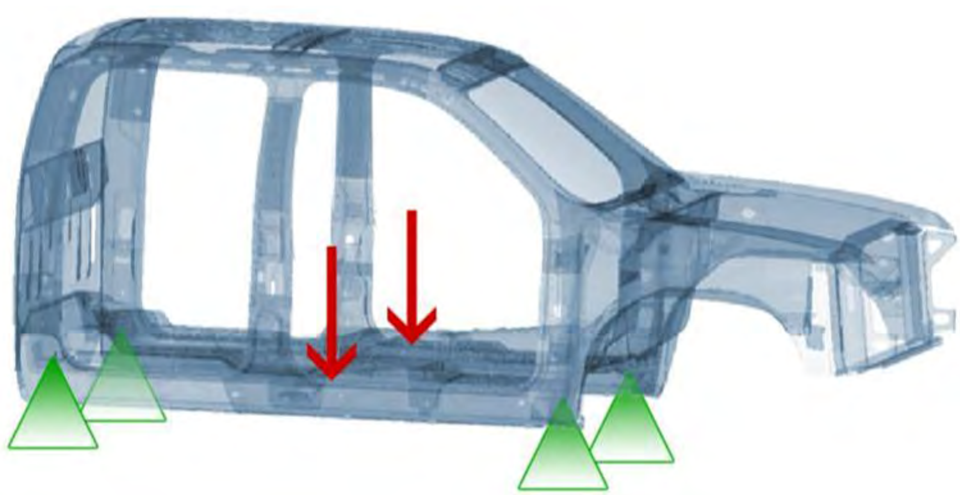


**Figure 2.3-23: Bending Stiffness CAE Setup**
*(Source: EDAG, Inc.)*

## Static Torsion Stiffness Test Setup

Similarly, the cabin was instrumented for measurement of torsion stiffness characteristics as shown in **Image 2.3-4**.

**Image 2.3-4: Torsion Stiffness Testing Setup**
*(Source: FEV, Inc.)*

The necessary deformations were measured at different test locations by applying 1,200N and -1,200N on the left and right front mounts respectively. The CAE model was created by incorporating the same boundary and loading conditions as seen in the physical test setup. **Figure 2.3-22** and **Figure 2.3-24** show the equivalent CAE model for the torsion stiffness test setup.

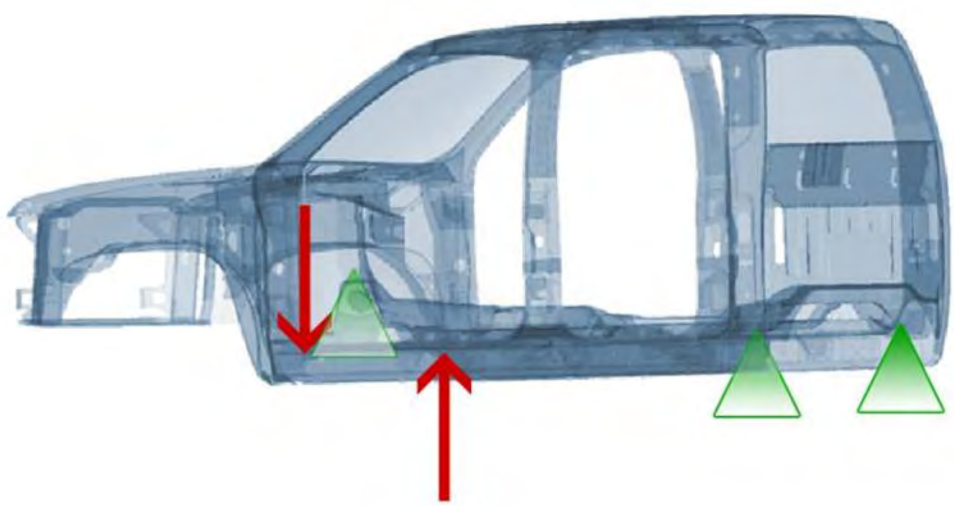


**Figure 2.3-24: Torsion Stiffness CAE Setup**
*(Source: EDAG, Inc.)*

**Step 2: EDAG CAE Baseline Model**

The Baseline NVH Cabin model was verified by the physical weight and material data. The test variants considered for the correlation were weight, global bending stiffness, and global torsion stiffness.

**NVH Correlation Summary**

Altair's Optistruct solver was used to analyze the NVH loadcases. The results of the NVH simulations were studied with respect to the test results. The correlation of the CAE test results of the cabin NVH load cases can be found in **Section 4.18**.

The same NVH baseline model was integrated accordingly to create the NVH modal, crash, and durability baseline models. The model setup and loadcase creations for these disciplines are explained later in this report.

*2.3.2.1.7.4 Cargo Box*

**Model Statistics**

The cargo box model consisted of the entire box parts welded, including cross-members, floor, wheel well, and box sides. The FEA model of the entire box assembly contained 32 parts made up of 113,254 shell and solid elements. The parts were connected by means of FE weld elements representing physical spot welds.

**Step 1: NVH Test Setup**

The necessary loadcase specific boundary conditions were incorporated into the corresponding model using commercially available pre- and post-processing tools and then analyzed using the Altair Optistruct solver. The model setup in terms of boundary and load conditions is explained in detail for each of the NVH loadcases. **Figure 2.3-25** shows the box model before incorporating the boundary and load conditions.

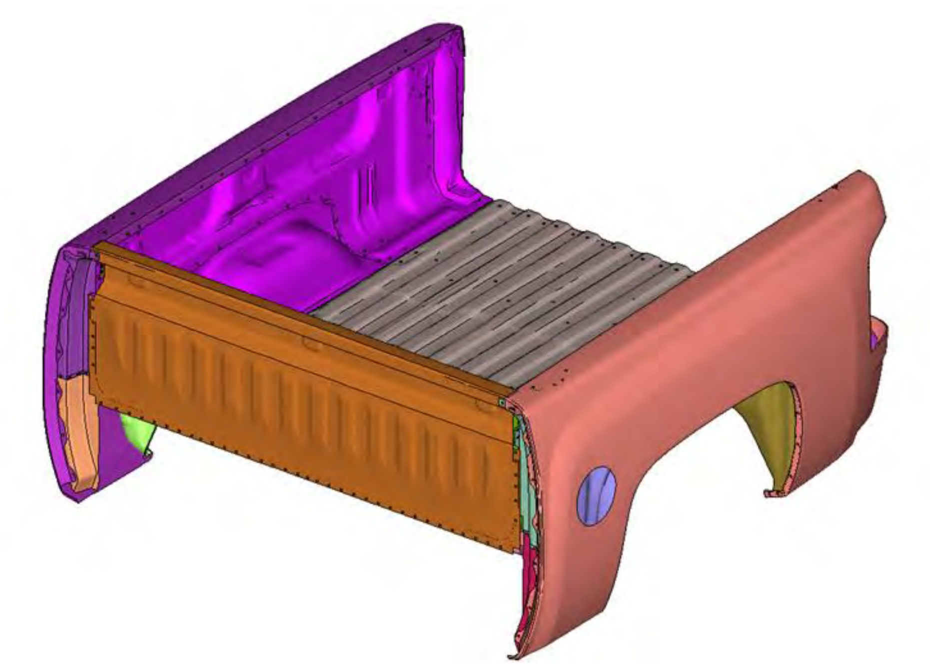


**Figure 2.3-25: Cargo Box NVH Model**
*(Source: EDAG, Inc.)*

### Static Bending Stiffness

In the bending stiffness model, the box was constrained and loaded as shown in **Figure 2.3-26**. The left-end of rear cross-member was constrained in the x-, y-, and z-axes; the right-end of rear cross-member was constrained in the x- and z-axes; the left-end of front cross-member was constrained in the y- and z-axes; and right-end of front cross-member was constrained in the z-axis. A bending load of 2,224N was applied at both left and right ends of the mid cross-member.

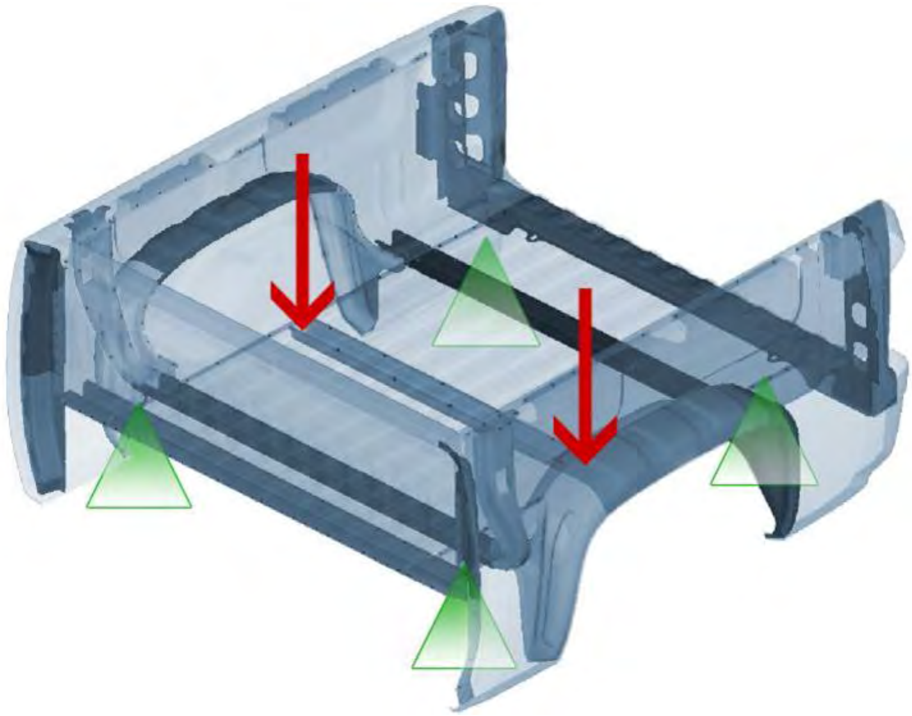


**Figure 2.3-26: Loads and Constraints on Cargo Box NVH Model for Bending Stiffness**
*(Source: EDAG, Inc.)*

The calculation of bending stiffness was done by measuring Z-displacement on the mid cross-member, noting the maximum displacement on each measured location.

$$Bending\ Stiffness = \frac{Total\ Force}{Maximum\ Displacement}$$

### Static Torsion Stiffness

The torsion stiffness box model was constrained and loaded, as shown in **Figure 2.3-27**. The left-end of rear cross-member was constrained in the x-, y-, and z-axes; the right-end of rear cross-member was constrained in the x- and z-axes. Additionally, the center of the front cross-member was constrained in the z-direction. Vertical loads of 1,200N were applied in opposite directions on the left and right-end of the mid cross-member. Torsional stiffness was calculated from the applied load and deflection.

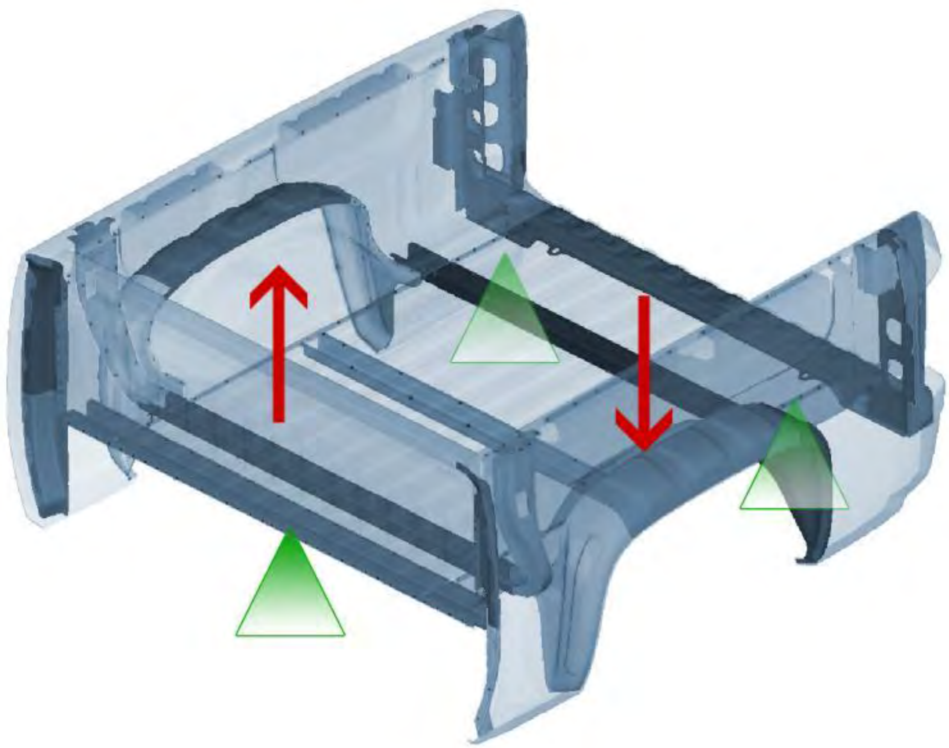


**Figure 2.3-27: Load and Constraints on Cargo Box NVH Model for Torsional Stiffness**
*(Source: EDAG, Inc.)*

The calculation of torsion stiffness was done by calculating the angular displacement of the box. The average of the Z-displacement (Z) at the mid cross-member is calculated, and then the distance between the left and right end of mid cross-member (D) was measured. The angular displacement (w) was calculated as ATAN (Z/D).

$$Torsion\ Stiffness = Total\ Force * Angular\ Displacement$$

## Step 2: EDAG CAE Baseline Model

The Baseline NVH cargo box model was verified by the physical weight and material data.

Altair's Optistruct solver was used to analyze the NVH load cases. The analytical NVH results for the cargo box can be found in **Section 4.18**.

*2.3.2.1.7.5 Full Body on Frame (BOF)*

**Model Statistics**

The full Body on Frame (BOF) model included frame, cabin, cargo box BIPs, front bumper, rear bumper and trailer hitch subsystems. The FEA model of the entire BOF contained 384 parts, made up of 756,554 shell and solid elements. The parts were connected by means of FE connection elements representing spot welds, seam welds, bolts, and bushings. The fully assembled body is shown in **Figure 2.3-28**. As discussed earlier, in this assembly, the frame is the same configuration as the 2011 Silverado frame, the cabin is the 2007 Silverado configuration (donor model) with updates from 2011 Silverado gauges, and the cargo box is same as the 2007 Silverado configuration (donor model).

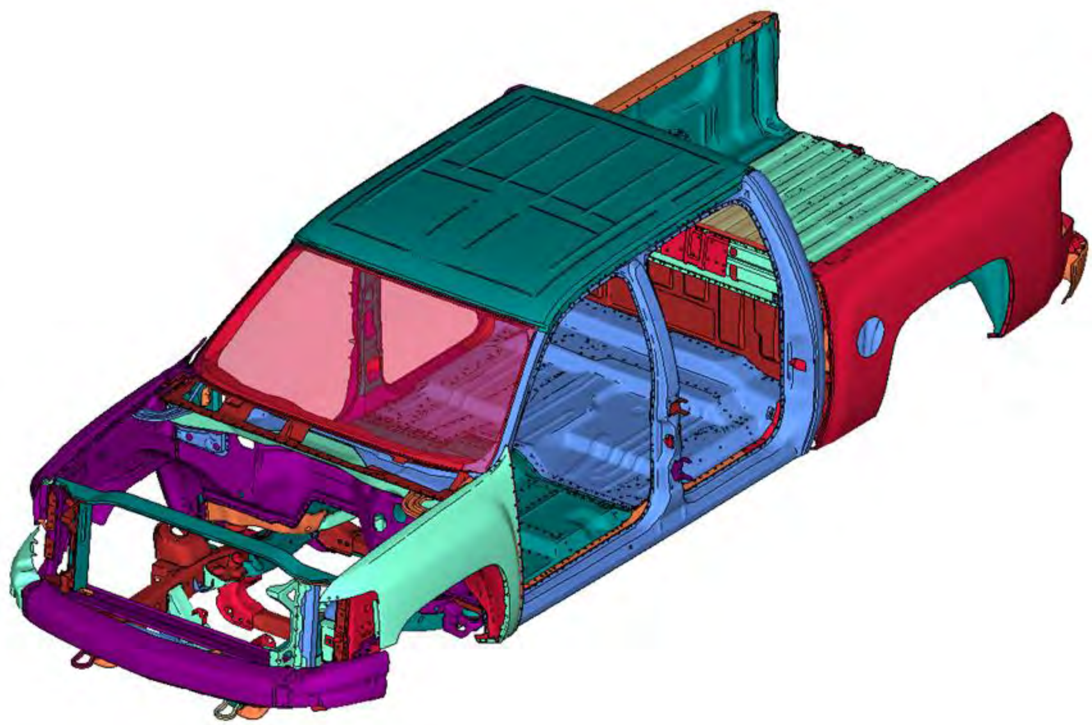


**Figure 2.3-28: Body on Frame NVH Model**
*(Source: EDAG, Inc.)*

The cabin was rubber mounted (with bushings) and the cargo box was hard mounted (bolted) on to the frame. There were eight bushing mounts connecting the frame and cabin together, four on either side of the vehicle. The bushings were located at the front end (Bushing #4), two at the rocker area under the cabin (Bushing #1 and Bushing #2), and another at the rear end (Bushing #3). The schematic representation of the bushings is shown in **Figure 2.3-29**.

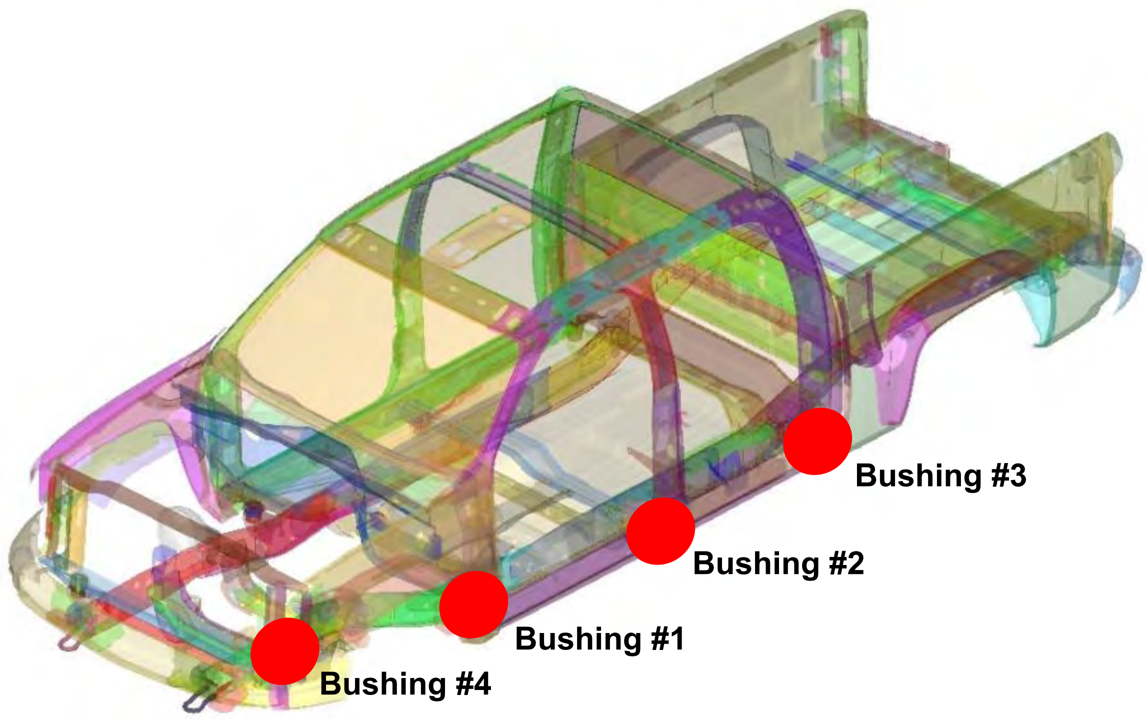
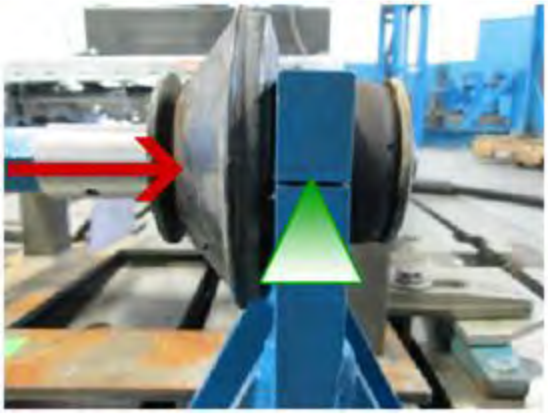



**Figure 2.3-29: Bushings in CAE Model**
*(Source: EDAG, Inc.)*

There were three types of bushings used; Bushing #4 at the front end is of the same type of Bushing #2. The bushing rates were determined by the push in/out test and torsion test. In the push in/out test, all bushings were pushed in/out statically as shown in **Image 2.3-5**. In the torsion test, a static torsion load was applied to all the bushings as shown in **Image 2.3-6**.



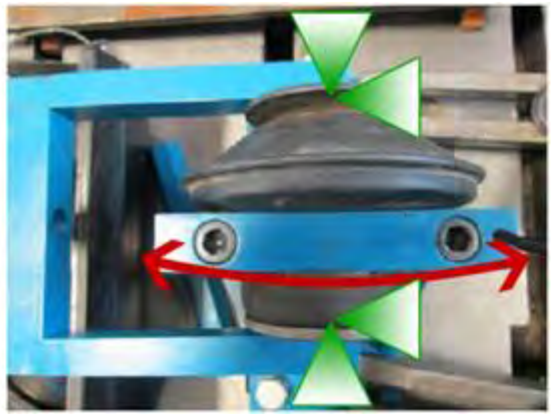


**Image 2.3-5 (Left): Push In/Out Test**

**Image 2.3-6 (Right): Torsion Test**

In both tests, bushings were loaded statically from 1.0 kN to 8.0 kN at the increment of 1.0 kN resulting in eight stiffness curves per bushing. Based on mass and load calculations, the stiffness curves at 3 kN load were used in CAE modeling. The bushing rates were assigned to the respective bushes. For discussion purpose, sample stiffness curves for bushing 1 are shown in **Figure 2.3-30** and **Figure 2.3-31**.

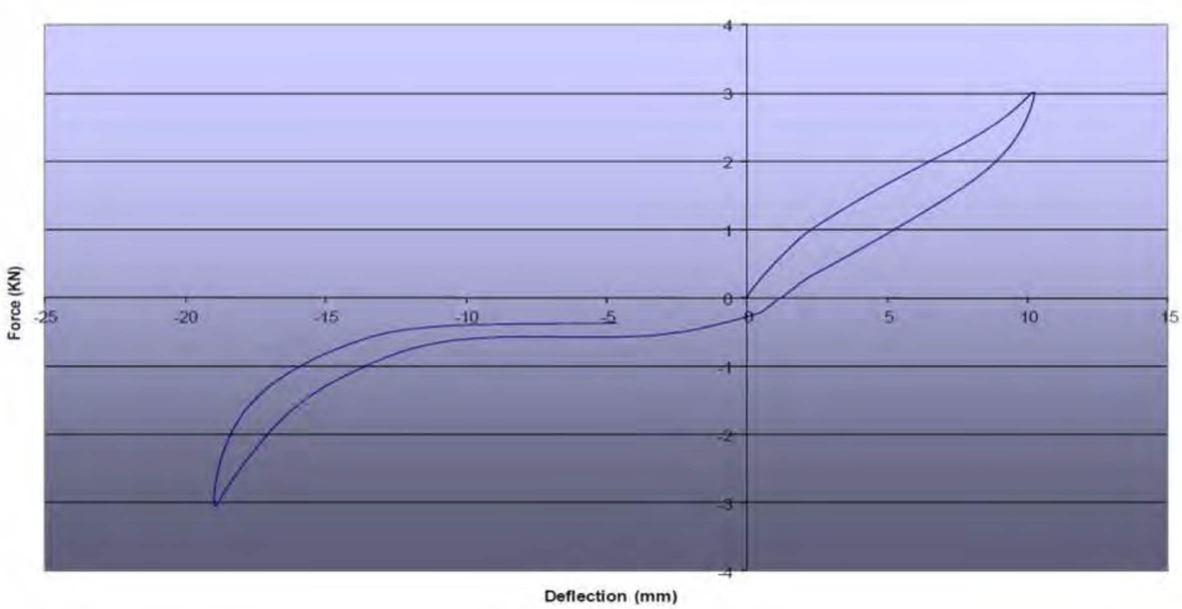



**Figure 2.3-30: Bushing #1 – Push In/Out Test Results**

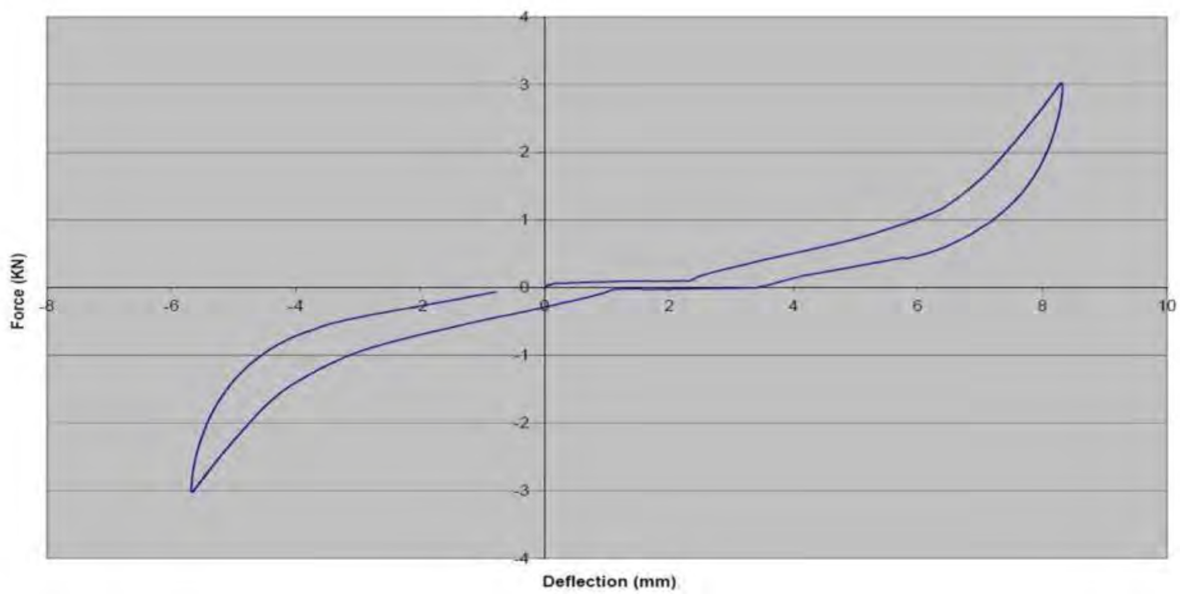



**Figure 2.3-31: Bushing #1 – Torsion Test Results**

The necessary loadcase specific boundary conditions were incorporated into the BOF model using commercially available pre- and post-processing tools and then analyzed using Altair's Optistruct solver. The model setup in terms of boundary and load conditions is explained in detail for each of the NVH loadcases.

### Static Bending Stiffness

In the bending stiffness BOF model, the frame was constrained and bending load was applied to the cabin as shown in **Figure 2.3-32**.The rear-left shock tower was constrained in the x-, y-, and z-axes; the rear-right shock tower was constrained in the x- and z-axes; the front left shock tower was constrained in the y and z-axes; and the front right shock tower was constrained in the z-axis. A bending load of 2,224N was applied to the cabin rocker/sill (both left and right side) at the center of front and rear seats just before the B-pillar.

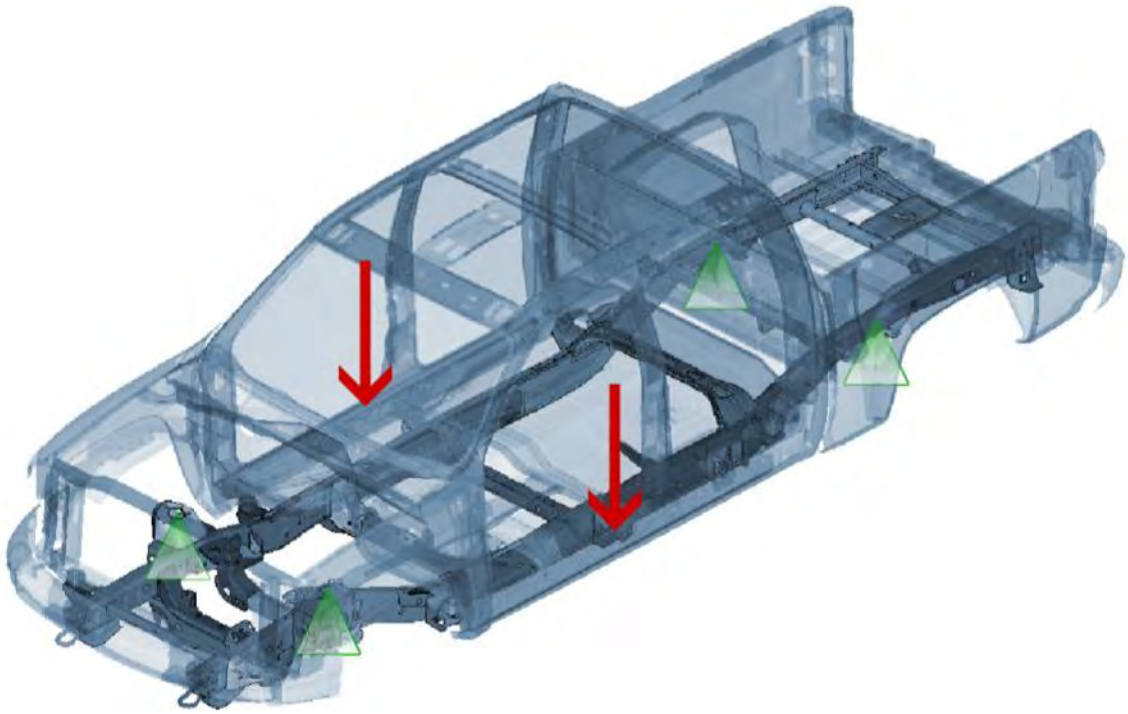


**Figure 2.3-32: Loads and Constraints on BOF NVH Model for Bending Stiffness**
*(Source: EDAG, Inc.)*

The calculation of bending stiffness was done by measuring Z-displacement on the mid rail of frame, noting the maximum displacement on each measured location.

$$Bending\ Stiffness = \frac{Total\ Force}{Maximum\ Displacement}$$

### Static Torsion Stiffness

In the torsion stiffness BOF model, frame was constrained and loaded, as shown in **Figure 2.3-33**. The rear-left shock tower was constrained in the x-, y-, and z-axes; the rear-right shock tower was constrained in the x- and z-axes. Additionally, the center of the front bumper was constrained in the z-direction. Vertical loads of 1,200N were applied in opposite directions on the left and right-front shock towers. Torsional stiffness was calculated from the applied load and deflection.

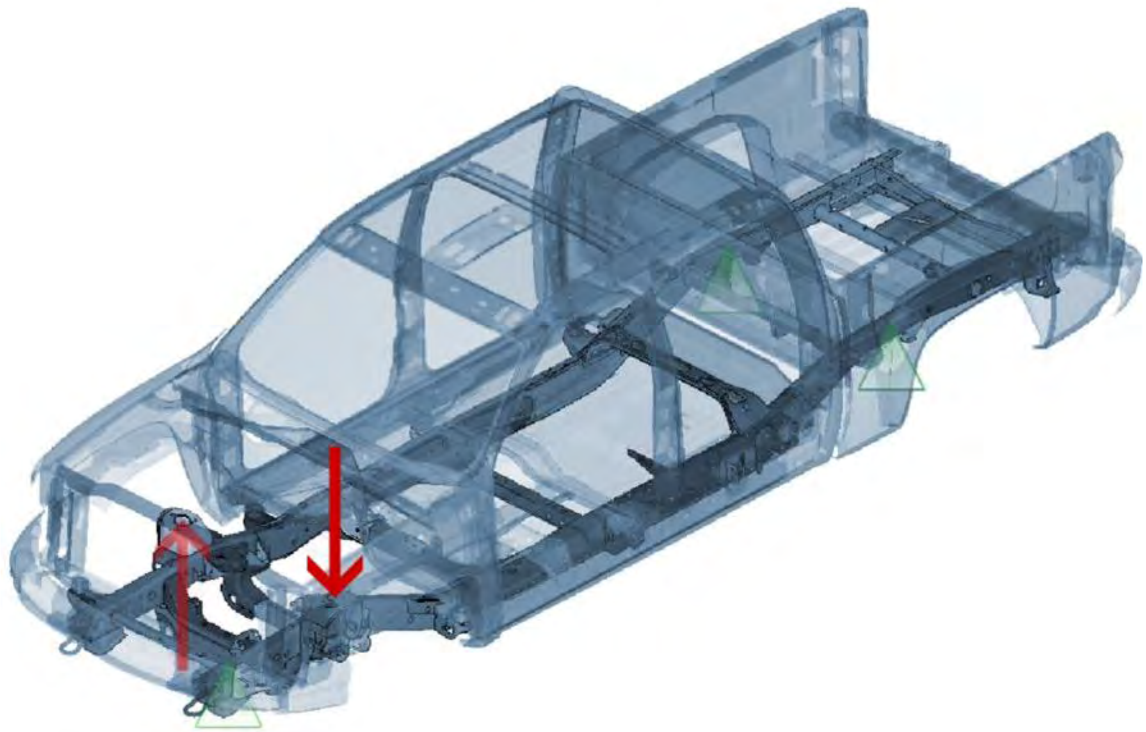


**Figure 2.3-33: Load and Constraints on BOF NVH Model for Torsional Stiffness**
*(Source: EDAG, Inc.)*

The calculation of torsion stiffness is done by calculating the angular displacement of the frame. The average of the Z-displacement (Z) at the front shock towers is calculated, and then the distance between the shock towers (D) is measured. The angular displacement (w) is calculated as ATAN (Z/D).

$$Torsion\ Stiffness = Total\ Force * Angular\ Displacement$$

### Step 1: NVH Test Setup

The BOF was setup with the necessary test equipment for static bending and static torsion measurements. The testing was conducted at the Ford Motor Company NVH labs.

### Static Bending Stiffness Test Setup

For testing purposes, the frame and cabin were instrumented with the necessary deformation measuring gages at the selected locations. The bending test setup is shown in **Image 2.3-7**. The deformations at different locations were measured by applying a 2,224N force at the left and right rocker sections of the front door openings of cabin.

**Image 2.3-7: Bending Stiffness Testing Setup**
*(Source: FEV, Inc.)*

With respect to the Silverado BOF, the CAE model was created as an exact replica of the test setup in order to achieve the test correlation. **Image 2.3-7** and **Figure 2.3-34** show the static bending CAE setup equivalent to the test vehicle.

**Figure 2.3-34: Bending Stiffness CAE Setup**
*(Source: EDAG, Inc.)*

### Static Torsion Stiffness Test Setup

Similarly, the vehicle was instrumented for measurement of torsion stiffness characteristics as shown in **Image 2.3-8**.

**Image 2.3-8: Torsion Stiffness Testing Setup**
*(Source: FEV, Inc.)*

The necessary deformations were measured at different test locations by applying 1,200N and -1,200N on the left and right front shock towers respectively. The CAE model was created by incorporating the same boundary and loading conditions as seen in the physical test setup. **Figure 2.3-35** shows the equivalent CAE model for the torsion stiffness test setup.

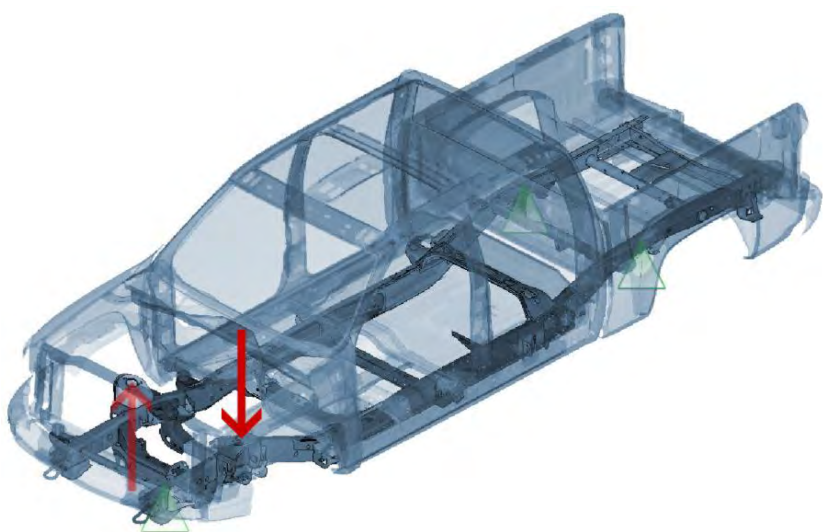


**Figure 2.3-35: Torsion Stiffness CAE Setup**
*(Source: EDAG, Inc.)*

**Step 2: EDAG CAE Baseline Model**

The Baseline BOF NVH model was verified by the physical weight and material data. The test variants considered for the correlation were weight, global bending stiffness, and global torsion stiffness.

**NVH Correlation Summary**

Altair's Optistruct solver was used to analyze the NVH loadcases. The results of the NVH simulations were studied with respect to the 2011 Silverado test results.

The correlation of the CAE test results of the BOF NVH load case is shown in **Section 4.18** along with the test results of the 2011 Silverado vehicle.

### 2.3.2.2 Phase 2: Definition of Comparison for Full Vehicle Crash

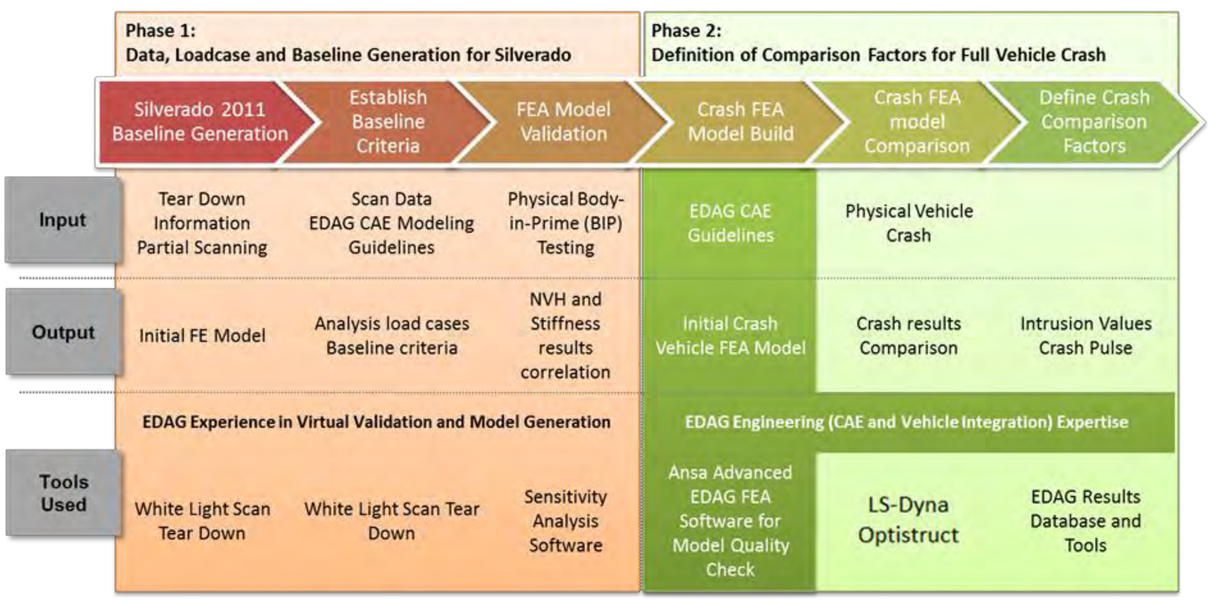



**Figure 2.3-36: Crash FEA Model Build**

#### 2.3.2.2.1 LS-DYNA Model Build

**I. Major System for Full Vehicle Model**

In order to build the full-vehicle crash model, the validated NVH BIP frame, cabin, and cargo box models (from **FEA Model Validation—Baseline NVH Model**) were utilized. Other components added to complete the baseline FEA model are listed in the following bullet points. The gauge map and material map of different modules including frame, cabin, cargo box, and closures are provided in **Silverado 2011 Baseline Generation**. The gauge and material data for the remaining structural assembly parts were also incorporated accordingly.

- Hood, doors, and tailgate for closures
- Front and rear bumper structural parts were also included to represent realistic high-speed front and rear-crash scenarios
- Powertrain assembly, major engine and transmission parts, radiator assembly, and exhaust system parts (all parts are critical to a high-speed frontal impact scenario)
- The fuel tank system parts (critical for rear and side-impact scenario)
- The rear seat subsystem was represented as a lumped mass (critical for front and rear-impact scenarios)
- An EDAG FEA seat system (integrated to take into account resistance of seat structure deformation in side-impact scenarios)

The full-vehicle crash model consisted of a total of 1,104,226 elements and was trimmed to a curb mass of 2,454 kg. The major systems of the full-vehicle crash model are built in a modularized approach as explained in Silverado 2011 Baseline Generation.

**Table 2.3-4: Contents of EDAG CAE Baseline Model**

| Model Detail | Count |
|---|---|
| Total number of shell elements | 1,057,178 |
| Total number of solid elements | 43,511 |
| Total number of beam discrete and misc. elements | 3,537 |
| **Total number of FE elements** | **1,104,226** |
| | |
| Total number of nodes | 1,137,108 |
| Total number of part IDs | 684 |

## II. Mass Validation

EDAG standard CAE Modeling guidelines[10] were followed throughout the model building process.

**Vehicle Mass:** Curb weight was 2,454 kg. For each loadcase, dummies and cargo was added per the test protocols. The appropriate number of dummies was added (modeled with simplified lumped mass and spring representations, using nominal instrumented dummy mass values) and the cargo mass was added, per the specific test protocols, as a rigid container in the center of the cargo box.

**CG:** The vehicle CG was calibrated to be also within approximately 1% of the test measurement. The main reason for the difference is that the CAE model contained many of the 2007 Silverado assemblies. It is important to note that the full vehicle CAE model was the EDAG developed model which was representative of a 2011 Silverado vehicle.

## III. FE Modeling Technique

There are many aspects of FE modeling that affects the accuracy of the simulation and the turn-around time of the numerous iterations required in the project. In order to meet the scope and timing of the project, it is critical to select these factors carefully so that the FE models will meet the requirements for simulation accuracy, consistency of the various iterations and additionally, provide the iteration turn-around time efficiency required.

Crash loadcases were simulated using LS-DYNA explicit time integration non-linear FE code. A partial list of the factors pertaining to LS-DYNA performance is presented below. These factors, and the resulting factors assigned to them, were determined by following the recent FE analysis trends and increasing the focus on factors that provide improved simulation accuracy. In part this is now possible by virtue of the enhanced computing power available today. However, it must also be noted some of these factors are still being debated throughout the automotive industry since the solver code and modeling techniques still have limitations in the correlation accuracy with physical tests.

### 1. Welding Property

The spot welds on the structure are represented using the mesh independent spot-weld beam weld elements. The material model used does not include spot-weld failure.

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### 2. Element Formulation

The element formulation in this BIW model is the LS-DYNA Type-16 fully-integrated Bathe-Dvorkin shell element for major load path parts.

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### 3. Integration Points

The integration point through the thickness of the sheet metal in this BIW model is used with the 5-point integration option for major load path parts.

### 4. Material Failure Criteria

The material models used for the structural parts did not include a damage or failure model.

#### 2.3.2.2.2 Baseline Crash Model Set-up

The CAE models are run over a number of NHTSA FMVSS crash tests using contractor confidential barrier models to prove out the CAE model versus actual vehicle crash data found in the NHTSA database. While the crash tests typically utilize dummy injury criteria to evaluate against a gage of parameters, the LS-DYNA models used in this study do not include occupant or restraint models so the performance is evaluated against structural performance metrics only. The metrics are a combination of the physical test metrics (e.g., intrusion in the NHTSA tests) and other measures selected to monitor the structural performance related to the loading on the occupants in each loadcase. Additional crash tests will be run to provide a baseline for those tests when comparing the results of the light weighted vehicle.

The selected loadcases are described briefly below. The baseline vehicle was evaluated to actual vehicle crash NHTSA data for frontal and side-impact loadcases. These loadcases were:

1. FMVSS 208—35mph, flat frontal crash with rigid wall barrier, same as the US New Car Assessment Program (US NCAP)
2. FMVSS 214—38.5mph,side impact with moving deformable barrier (MDB) at 27 degrees, same as US Side Impact New Car Assessment Program (US SINCAP)
3. FMVSS 214 Pole—20mph, 5th Percentile, side impact with rigid pole barrier at 15 degrees

Once acceptable results were obtained in these crash load cases additional crash simulations were run to further enhance the baseline model and provide additional comparisons for the potential light weight solutions. These load cases included:

1. Insurance Institute for Highway Safety (IIHS)—40mphfrontal crash with Offset Deformable Barrier (ODB)
2. Insurance Institute for Highway Safety (IIHS)—31mph, side impact with moving deformable barrier (MDB) at 90° degrees
3. FMVSS 301—50mph, rear impact with moving deformable barrier (MDB)
4. FMVSS 216a—Roof crush resistance (utilizing the higher standard IIHS roof crush resistance criteria)

**Figure 2.3-37** shows six different loadcase configurations, IIHS MDB is not shown, with appropriate barriers placed against the full vehicle baseline model.

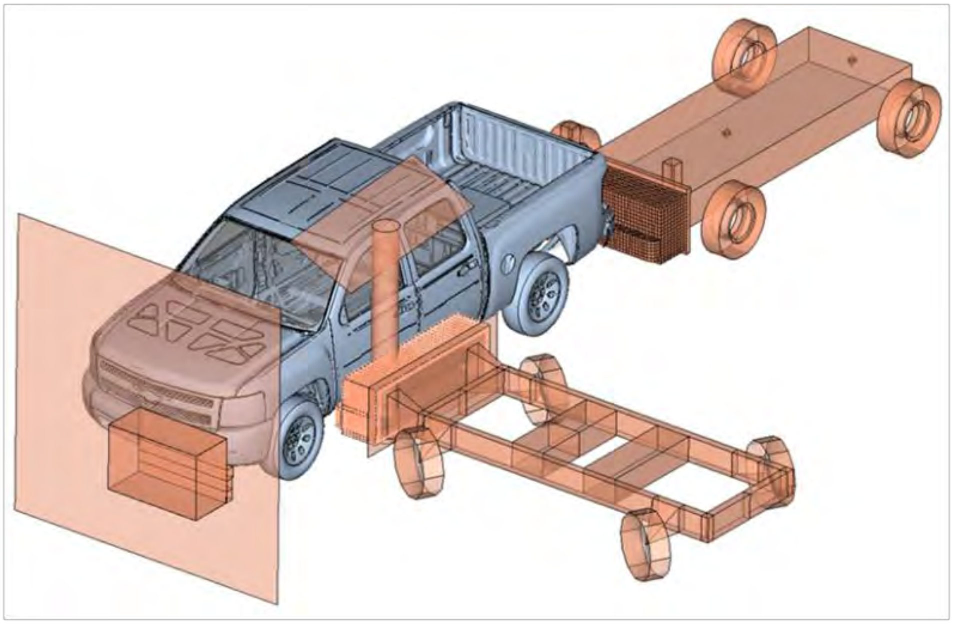

**Figure 2.3-37: Baseline Crash Model Evaluation**
*(Source: EDAG, Inc.)*

***Note: IIHS Small Overlap being evaluated on the lightweight vehicle in a separate effort with Transport Canada and EDAG.***

### 2.3.2.3 Phase 3: Modularization and System Analysis

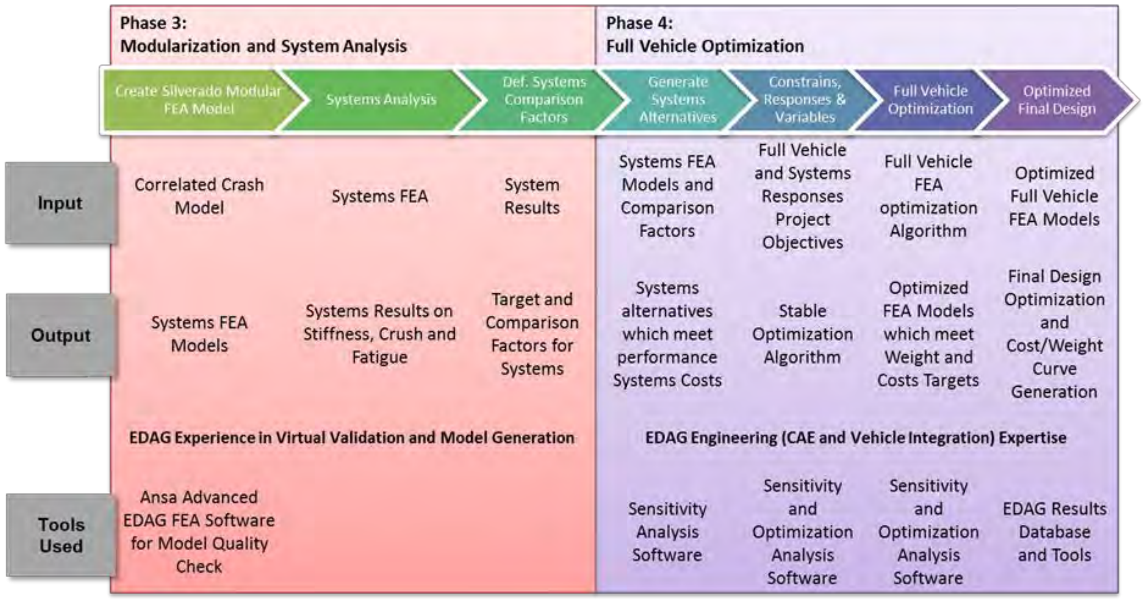


**Figure 2.3-38: Create Modular FEA Models**

This section under Phase 3 of the light-weight design optimization process explains the baseline stage of full vehicle integrated optimization and the remaining subsystem analyses.

#### 2.3.2.3.1 Create Silverado Modular FEA Models

As described previously, the full vehicle model was built in subsystems modules. The validated crash model was further refined to be compatible with subsystem parameterization and plug-and-play integration techniques. Altair's Optistruct and LS-DYNA approaches for module management by means of "INCLUDE" statements were utilized accordingly for NVH/Durability and Crash loadcases. Light weighting strategies and applicable subsystem level variations were considered while grouping the subsystems. **Figure 2.3-39** shows typical subsystem modules built for body-on-frame type of vehicle.

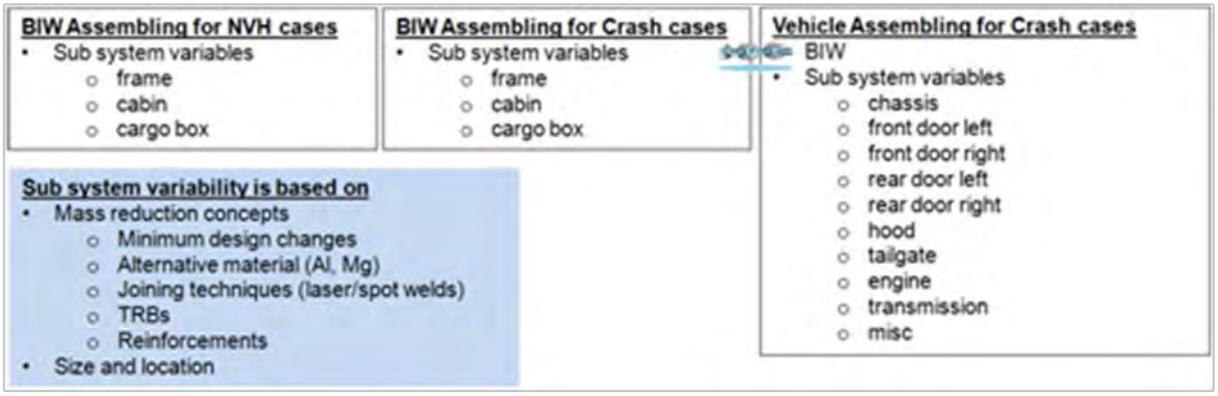


**Figure 2.3-39: Subsystems Grouping**

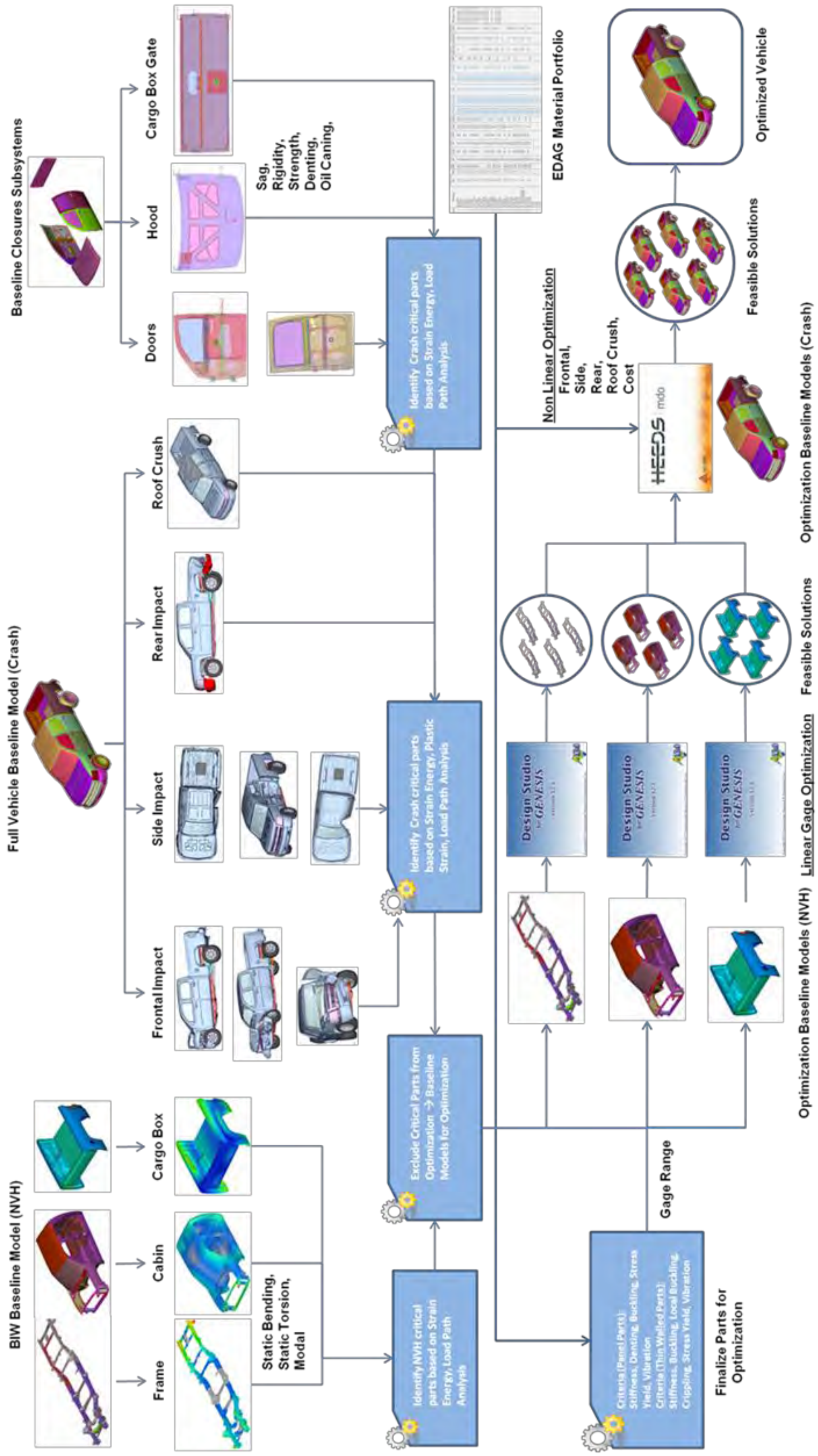


**Figure 2.3-40: Subsystems to Full Vehicle Integrated Optimization**

The process flow (**Figure 2.3-40)** starts with identifying the necessary parts from each subsystem, and full-vehicle loadcases, by analyzing the respective performance criteria. Once the parts are identified, the subsystem analysis is carried out by considering NVH and durability performance targets first to obtain all feasible combinations of material grade and gauge. The feasible designs are in the form of subsystem models with reduced weight and with the same or better performance compared to the baseline models. The feasible designs are then integrated as input parameters into the full vehicle non-linear optimization. Thus the collaborative trade off process involves the following stages:

**Stage 1: Subsystem analysis:**

Identify parts that can be optimized to reduce the most weight from each loadcase such as:

- Body subsystems - Static bending, static torsion, and dynamic modal
- Closure subsystems - Rigidity, strength, denting, oil canning, and sag.
- Full vehicle - Frontal, side, rear, and roof-crush

Determine the range of optimization parameters from subsystem analysis. The loadcases involved are:

- Body subsystems - Static bending, static torsion, and dynamic modal
- Closure subsystems - Rigidity, strength, denting, oil canning, and sag

Obtain feasible subsystem models.

**Stage 2: Full vehicle integrated analysis:**

- Integrate feasible subsystem models from Stage 1 as input parameters
- Establish minimum and maximum range of material grade and gauge for each part
- Establish full vehicle performance and cost constraints

**Stage 3: Human intelligence:**

Inject updated designs as new inputs to the optimization due to the following:

- Design change of parts not originally included in the process/analysis (e.g., Powertrain, Chassis)
- Change of joining technology

**Stage 4: Apply additional weight reduction strategies:**

Obtain models from Stage 3, the output of full vehicle integrated analysis and trade off.

- Optimize performance by iterating joining technologies
- Material replacement with alternative materials within the manufacturability constraints
- Optimize by utilizing alternative manufacturing technologies such as tailor rolled blank (TRB) or tailor welded blank (TWB), etc.

2.3.2.3.2 System Analysis

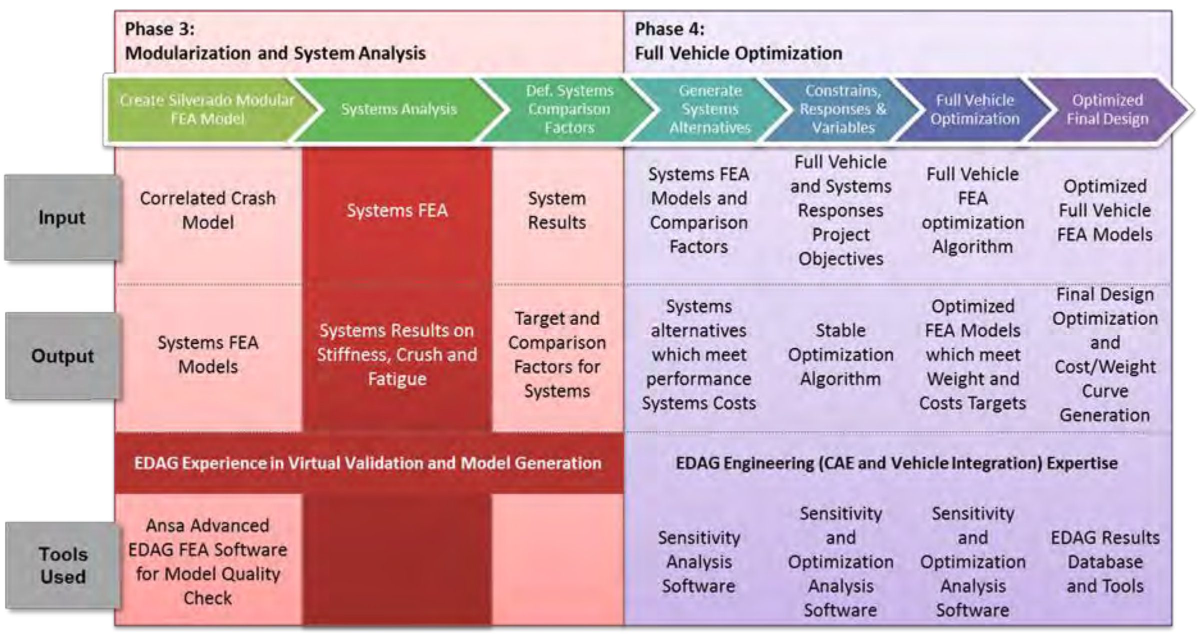


**Figure 2.3-41: Systems Analysis**

Subsystem analysis is carried out for two reasons: 1) weight opportunities of the subsystem itself with subsystem performance targets, and 2) determining the minimum and maximum range of material grade and gauge values to be used in further full vehicle optimization.

Out of all the subsystems explained in earlier sections, the system analysis for Frame, Cabin, and Cargo Box were performed for NVH load cases and obtained the baseline results. In the results section (**Section 4.18.3**) the system analysis of the remaining subsystems (closures) are explained with NVH strength and stiffness load cases to establish baseline models. The targets for performance included in the tables are based on past EDAG experience for closures of a similar size and construction.

#### 2.3.2.4 Phase 4: Full Vehicle Optimization

##### 2.3.2.4.1 Lightweight Design Optimization Overview

The project scope included the objective of investigating lightweight design possibilities of the baseline vehicle and the costs associated with them. It consisted of optimizing and modifying the design of the baseline model in systems and subsystems such as frame, body structure, closures, and bumpers.

EDAG expertise processes and standards on lightweight optimization processes were followed throughout this project phase. CAE-based Multi-disciplinary Optimization (MDO) was carried out by including load cases of regulatory safety requirements and structural performance standards previously described in this report. The typical lightweight optimization process followed in this project is shown in **Figure 2.3-42**.

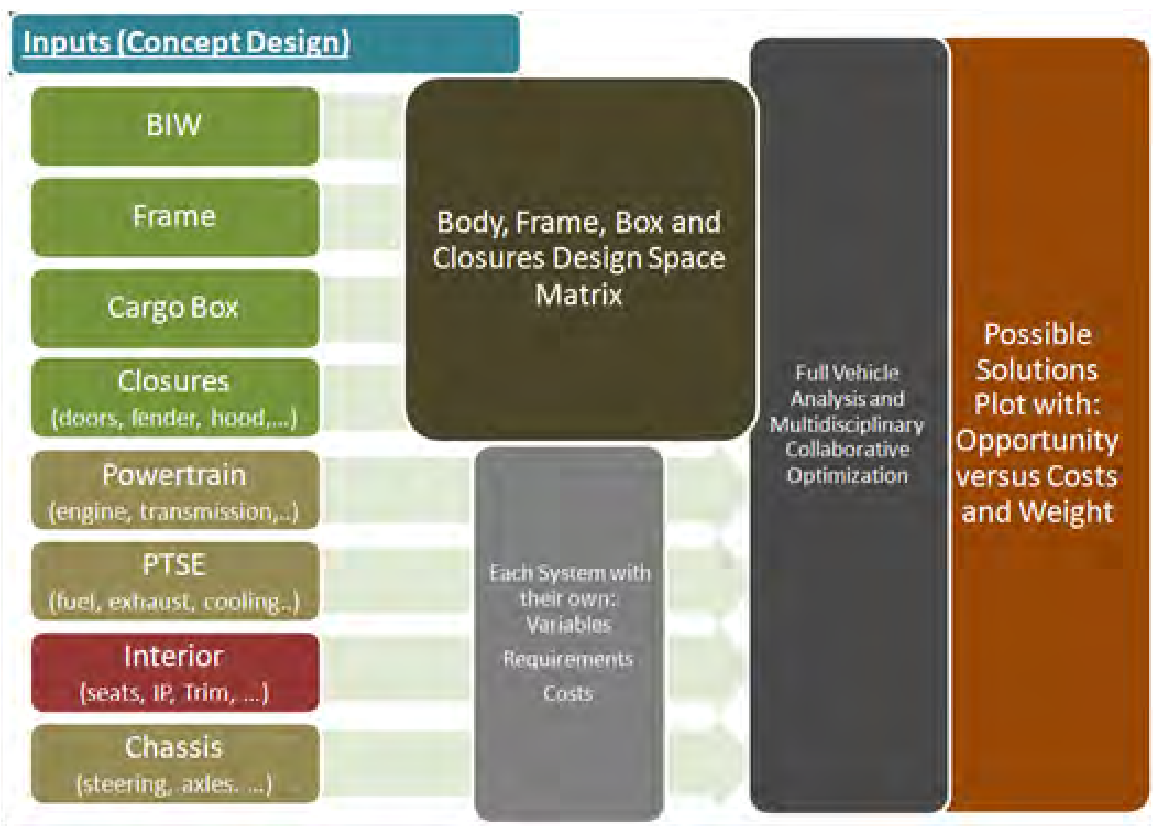


**Figure 2.3-42: Lightweight Design Optimization Process**

### 2.3.2.4.1.1 *Lightweight Design Strategy*

The overall principles followed during the study included:

- Minimize cost impact
- Minimize the use of exotic materials (carbon fiber, titanium, composites, etc.)
- Minimize the use of non-proven manufacturing technology
- Minimize the amount of redesign, retooling, or new processing

#### 2.3.2.4.1.1.1 Materials

Due to the technical advancements in steels (High Strength Steels [HSS]) and Advanced High Strength Steels [AHSS]) and opportunities of other materials such as aluminum, magnesium, composites, etc., weight reduction by material replacement is one of the avenues utilized in this project.

For steel, the material (grade) replacement (HSS, AHSS, etc.) allows making the vehicle components lighter with reduced material thickness (gauge) and for aluminum and magnesium, light weighting would be achieved by the materials of lower density [11,12], and volume to maitain performance requirments. These changes would affect the structural performance, crash worthiness, and occupant safety requirements and so when looking at alternative materials in the vehicle, partial or complete redesigning or shape change (geometry) of the components is necessary to maintain the regulatory safety requirements as well as the manufacturer's structural performance standards. Geometry changes can also be large scale load path optimization and suggest a new design for the body-in-white (BIW).

#### 2.3.2.4.1.1.2 Cost

Selection of high strength, lightweight materials can result in material cost increase depending on the grade and quantity of materials selected, amount of redesign efforts, etc. Changes in production methods may result in some cost savings. The right balance

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11 Chang, David Justusson, William J., "Structural Requirements in Material Substitution for Car-Weight Reduction", SAE 1976.

12 Cheah, Lynette., "Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S.", MIT 2010.

between weight reduction and cost increase is always the challenge in lightweight vehicle design.

#### 2.3.2.4.1.1.3 Methodology

Optimization and trade-off techniques have been developed to evaluate these diverse scenarios. In case of vehicle light weight design, the three structural parameters; material Grade, Gauge and Geometry (3G) and one Cost (C) parameter need to be iterated while targeting the optimum(s) weight reduction without compromising structural and crash/safety performance requirements. Based on EDAG lightweight optimization process standards and research materials [13, 14], the following weight reduction strategy was carried out:

- Change material gauges and grades for steel
  - Vary the combinations of part thicknesses and material grades within allowable limits
- Apply alternative materials
  - Use aluminum alternatives for panel parts (closures) and bumpers
  - Use aluminum alternatives for structural parts and subsystems
- Change joining technologies
  - Convert spot-weld connections into laser-weld connections on the body structure
  - Use of adhesives or bonding technologies
- Explore alternate manufacturing technologies
  - Use tailor rolled blanks (TRB) instead of tailor welded blanks (TWB)
  - Use of hydro forming technology
- Geometry changes
  - Make minimum, if any, design changes needed to meet the performance targets
- Manufacturability constraints
  - Incorporate simultaneously the manufacturability of the parts that are undergoing the changes, in each stage of the optimization process
- Cost constraints
  - Analyze cost impact due the changes in the optimization process

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13 "Ultra-Light Steel Auto Body report by Porsche Engineering Service, Inc. for Phase I and Phase II Findings," March 1998 published by ULSAB Consortium.

14 Pavel Brabec, Miroslav Maly, and Robert Vozenilek, "Experimental Determination of a Powertrain's Inertia Ellipsoid."

Even though by redesigning the body parts (geometry change) the potential for weight reduction increases, geometry changes were not part of the project scope, and weight optimization was carried out without undertaking major design changes. Only grade and gauge changes were mostly made (2G).

#### 2.3.2.4.2 Generate Systems Alternatives

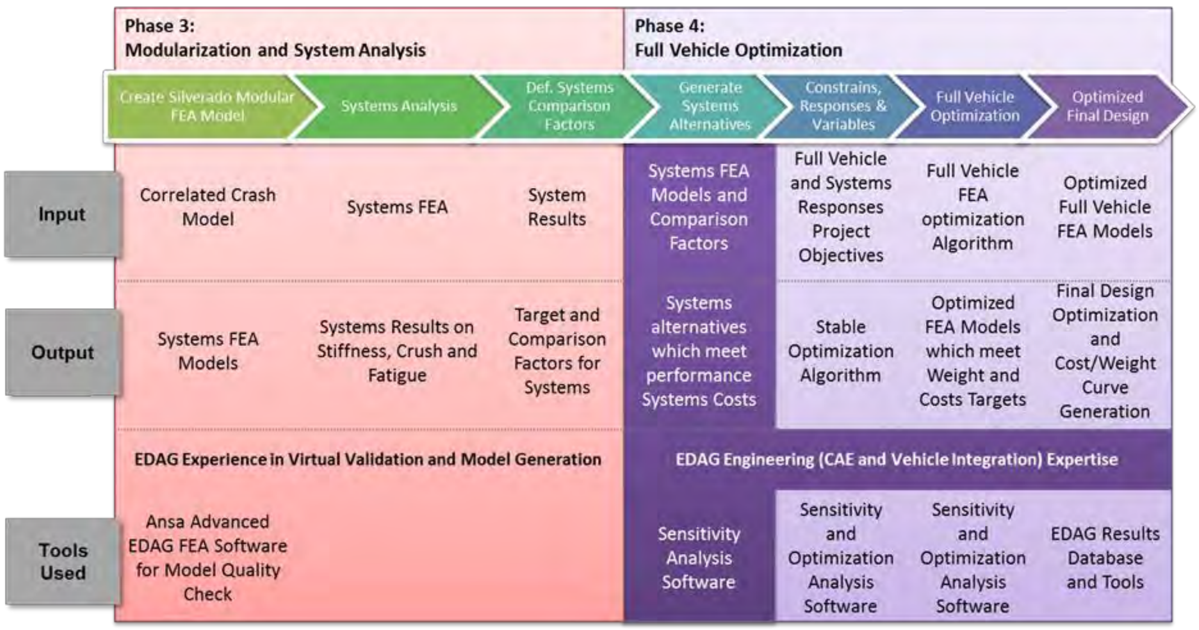


**Figure 2.3-43: Generate Subsystems Alternatives**

Once the baseline models and targets were obtained for each subsystem, various alternatives (feasible designs) were attempted to develop a library for each subsystem. These subsystem libraries were later integrated to full vehicle optimization as variables (subsystems) while executing the optimization cycle. In this section, various strategies of developing such systems alternatives are explained.

First, at the subsystem level, 2GC optimization and CAE simulations were carried out for the corresponding applicable loadcases.

#### *2.3.2.4.2.1 Change Material Grades and Gauges*

##### 2.3.2.4.2.1.1 Subsystem 2GC Optimization

The individual subsystems were evaluated for 2GC using approved CAE processing tools. The optimization variables for 2GC optimization process were material grade and part thickness. The constraints were the target performance metrics such as body bending stiffness, torsion stiffness, modal frequencies, closures and panel deformations, and material cost. In order to reduce the analysis cycle time, commercially available optimization tools Genesis and HEEDS MDO were used depending on the linear or non-linear characteristics of the loadcases.

##### 2.3.2.4.2.1.2 Subsystem Iteration

In addition, each subsystem was manually iterated for high-strength material utilization, alternative material replacement (aluminum, magnesium, etc.), change of joining technologies, and using TRB/TWB accordingly. The main purpose of these iterations was to improve subsystem performance to extend the weight reduction potential in the full vehicle optimization stage.

#### *2.3.2.4.2.2 Material Changes*

##### 2.3.2.4.2.2.1 Steel (HSS/AHSS)

The subsystems explained in the previous sections were analyzed to improve their performance by including HSS and AHSS materials. A list of HSS and AHSS considered in developing subsystem alternatives is provided in **Table 2.3-5**.

**Table 2.3-5: HSS and AHSS Subsystem Alternatives**

| Item # | Steel Grade | Thickness (mm) Min t | Thickness (mm) Max t | Gage Length | YS (Mpa) Min | YS (Mpa) Typical | UTS (Mpa) Min | UTS (Mpa) Typical | Tot EL (%) Typical | N-value Typical | Modulus of Elasticity (Mpa) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | DP 300/500 | 0.5 | 2.5 | A80 | 300 | 345 | 500 | 520 | 30-34 | 0.16 | $20.6 \times 10^4$ |
| 2 | HSLA 350/450 | 0.5 | 5.0 | A80 | 350 | 360 | 450 | 470 | 23-27 | 0.16 | $21.8 \times 10^4$ |
| 3 | DP 350/600 | 0.6 | 4.0 | A80 | 350 | 385 | 600 | 640 | 24-30 | 0.19 | $21.3 \times 10^4$ |
| 4 | TRIP 350/600 | 0.6 | 4.0 | A50 | 350 | 400 | 600 | 630 | 29-33 | 0.20 | $21.0 \times 10^4$ |
| 5 | DP 400/700 | 0.6 | 4.0 | | 400 | | 700 | | 19-25 | 0.14 | $21.0 \times 10^4$ |
| 6 | TRIP 400/700 | 0.8 | 4.0 | | 400 | | 700 | | 24-28 | | $21.0 \times 10^4$ |
| 7 | HSLA 420/500 | 0.76 | 5.0 | | 420 | 430 | 500 | 530 | 22-26 | | $21.0 \times 10^4$ |
| 8 | FB 450/600 | 1.8 | 5.0 | A80 | 450 | 530 | 560 | 605 | 18-23 | 0.11 | $22.4 \times 10^4$ |
| 9 | TRIP 450/800 | 0.9 | 2.0 | A80 | 450 | 550 | 800 | 825 | 26-32 | 0.24 | $20.1 \times 10^4$ |
| 10 | HSLA 490/600 | 0.75 | 5.0 | | 490 | 510 | 600 | 630 | 20-25 | 0.13 | $21.0 \times 10^4$ |
| 11 | TWIP 500/980 | 0.8 | 2.0 | A50M | 500 | 550 | 980 | 990 | 60 | 0.4 | $18.8 \times 10^4$ |
| 12 | CP 500/800 | 0.8 | 2.0 | A80 | 500 | | 800 | | 10-14 | | $21.0 \times 10^4$ |
| 13 | DP 500/800 | 0.6 | 4.0 | A50 | 500 | 520 | 800 | 835 | 14-20 | 0.14 | $21.2 \times 10^4$ |
| 14 | HSLA 550/650 | 0.75 | 5.0 | A50 | 550 | 586 | 650 | 676 | 19-23 | 0.12 | $21.2 \times 10^4$ |
| 15 | SF 570/640 | | | | 570 | | 640 | | 20-24 | 0.08 | $21.0 \times 10^4$ |
| 16 | SF 600/780 | 2.9 | 5.0 | A50 | 600 | 650 | 780 | 830 | 20-24 | | $21.0 \times 10^4$ |
| 17 | DP 700/1000 | 0.6 | 2.3 | A50 | 700 | 720 | 1000 | 1030 | 12-17 | 0.09 | $21.0 \times 10^4$ |
| 18 | CP 800/1000 | 0.8 | 3.0 | A80 | 800 | 845 | 1000 | 1005 | 8-13 | 0.11 | $22.9 \times 10^4$ |
| 19 | MS 950/1200 | 0.5 | 3.2 | A50M | 950 | 960 | 1200 | 1250 | 5-7 | 0.07 | $20.8 \times 10^4$ |
| 20 | CP 1000/1200 | 1.0 | 2.3 | | 1000 | 1020 | 1200 | 1230 | 8-10 | | $21.0 \times 10^4$ |
| 21 | CP 1050/1470 | | | A50M | 1050 | 1059 | 1470 | 1495 | 11 | 0.04 | $21.5 \times 10^4$ |
| 22 | HF 1050/1500 (22MnB5) | | | | | | | | | | |
| 23 | DP1150/1270 | | | A50M | 1150 | | 1270 | 1271 | 9 | 0.118 | $21.5 \times 10^4$ |
| 24 | MS 1150/1400 | 0.5 | 2 | A50 | 1150 | 1200 | 1400 | 1420 | 4-7 | | $21.0 \times 10^4$ |
| 25 | MS 1250/1500 | 0.5 | 1.5 | A50M | 1250 | | 1520 | | 3-6 | 0.07 | $21.0 \times 10^4$ |

When the low-strength steel materials (steel materials with lower yield strength such as Mild Steel) are changed to high-strength steel materials (steel materials with higher yield strength such as HSLA Steel), the respective part thickness is modified accordingly to maintain the performance level. Each subsystem was subjected to change of higher grade materials and part thickness based on engineering analysis and EDAG optimization techniques. CAE simulations were carried out for the subsystem-specific loadcases to verify the performance compliance to be same or better than baseline targets.

#### 2.3.2.4.2.2.2 Aluminum

Alternative material choices for an automobile's body structure have been increasingly one of the considerations in building a lightweight vehicle. Aluminum-based materials are proven for their better strength:weight ratio equivalent when compared to steel-based materials[15]. They are, therefore, good replacements for the steel grades of bigger panels.

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15 Advance, Lightweight Materials Development and Technology for Increasing Vehicle Efficiency by KVA Inc. Dec. 2008

Considering the cost and manufacturing constraints, the carefully selected parts of various systems were changed to aluminum-grade materials.

The thickness was changed by incorporating EDAG expertise and performing further CAE simulations while at the same time also meeting structural and crash performance targets. This option was further supported by the work done by the Superlight-Car[16] projects. Three of the major subsystems that utilized aluminum changes are shown in **Figure 2.3-44** through **Figure 2.3-46**.


**Figure 2.3-44: Aluminum used in the Frame**
*(Source: EDAG, Inc.)*

16 Dr. Marc Stehlin, SuperLight-Car, Volkswagen Group Research, under Sustainable Production Technologies of Emission Reduced Light Weight Car Concepts, April 2008.

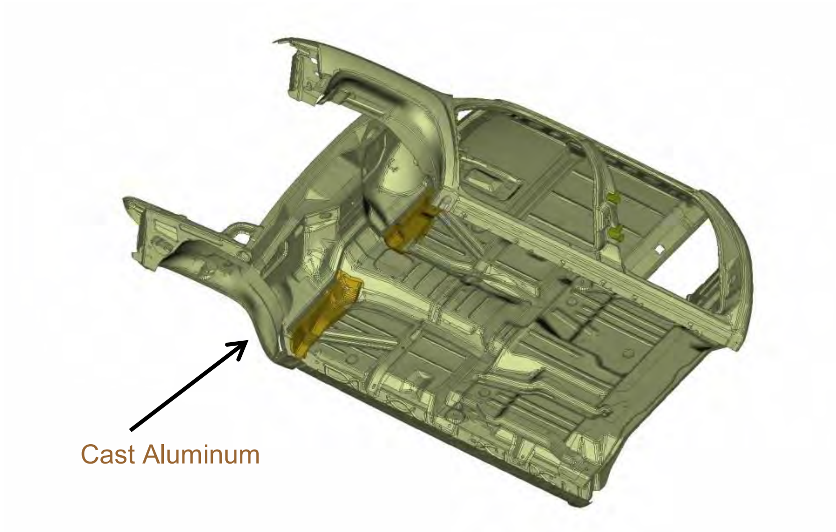


**Figure 2.3-45: Aluminum used in the Cabin**
*(Source: EDAG, Inc.)*

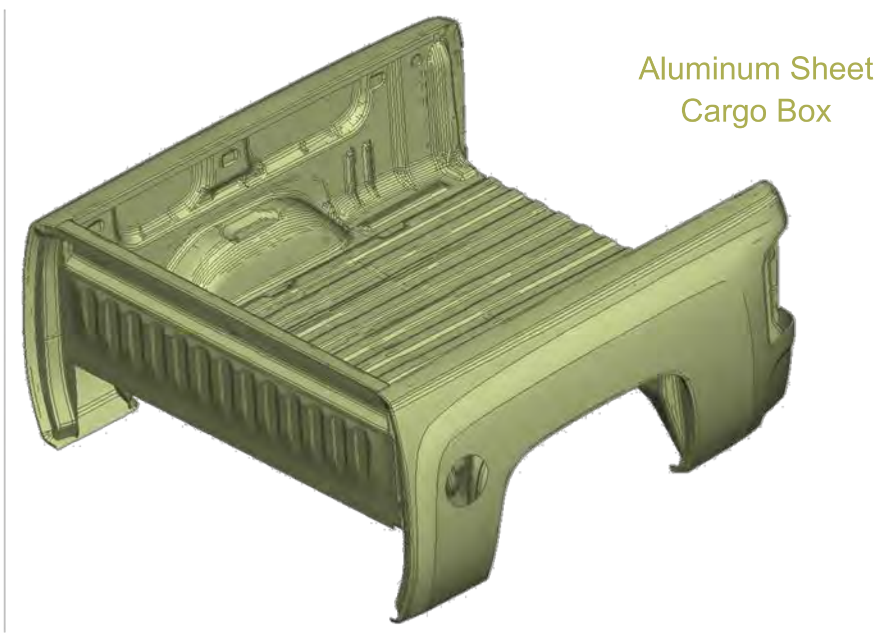


**Figure 2.3-46: Aluminum used in the Cargo Box**
*(Source: EDAG, Inc.)*

### *2.3.2.4.2.3 Alternative Joining Technology*

#### 2.3.2.4.2.3.1 Steel Joining

In the process of lightweight optimization to obtain subsystem alternatives, an exploration was made into the alternative joining technologies for part assembly. One of the options considered was changing spot welds to laser welds on frame, cabin, and cargo box. The potential areas of applying laser welding were identified at the tailor rolled blanks (TRB) replacement areas. The alternatives developed by this approach were the combination of laser welds and tailor rolled blank parts. The subsystem development by tailor rolled blank changes is explained in the following Alternative Manufacturing Technology section

2.3.2.4.2.3.2 Aluminum Joining

The proposed BIW construction combination of self-piercing rivets (SPR) and bonding with pressed aluminum panels and aluminum castings.

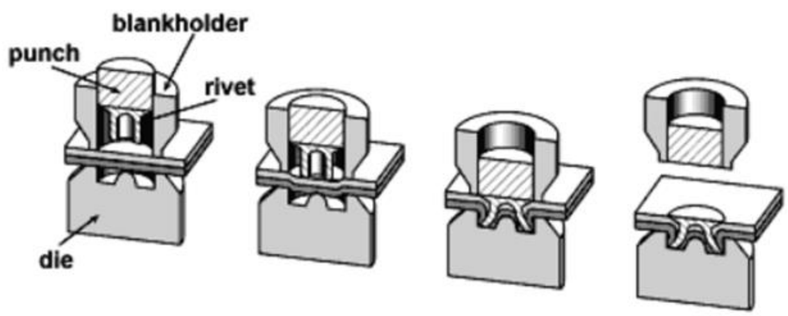


**Figure 2.3-47: SPR Sequence**

The process for SPR is currently used in high-volume manufacturing at Jaguar Land Rover, Audi, and other OEMs.

2.3.2.4.2.3.3 Adhesives

The other important joining technology for aluminum body designs is adhesive bonding. The properties of joints can be significantly improved by use of heat cured epoxy adhesives. Normally adhesive bonds are applied in a linear form. Such joints exhibit excellent stiffness and fatigue characteristics, but should be used in conjunction with spot welding, riveting or other mechanical fastening methods in order to improve resistance to peel in large deformation (i.e., during crash). Also, surface pretreatment is necessary for long term durability of adhesively-bonded structural joints.

*2.3.2.4.2.4 <u>Alternative Manufacturing Technology</u>*

Recent advancements in manufacturing technologies led to the conclusion that alternative manufacturing options should also be included in the lightweight design process. One such technology is the manufacturing of hot stamped parts of varied thicknesses using tailor rolled blanks (TRB). In this technology, the blank is prepared by a special rolling process which can produce varied thicknesses along the length of the blank without needing any seam or laser welding or trimming processes. This is considered to achieve better structural strength against weight of the part. For a baseline body structure, the parts of tailored welded blanks (TWB) are good choices. Accordingly, considering the cost impact, potential TWB parts were identified and assessed for the possibility of producing the same parts using TRBs. Frame rails, Cabin A-pillar, B-pillar, roof rails, and seat cross members were assessed by using TRB technology. Out of several alternatives explored within frame, cabin, and cargo box subsystems, the frame alternative was found to be a feasible design. The TRB part replaced at the mid and rear, inner and outer rail parts as shown in **Figure 2.3-48** and the rolled gauge transition of the TRB is also shown in **Figure 2.3-49**.

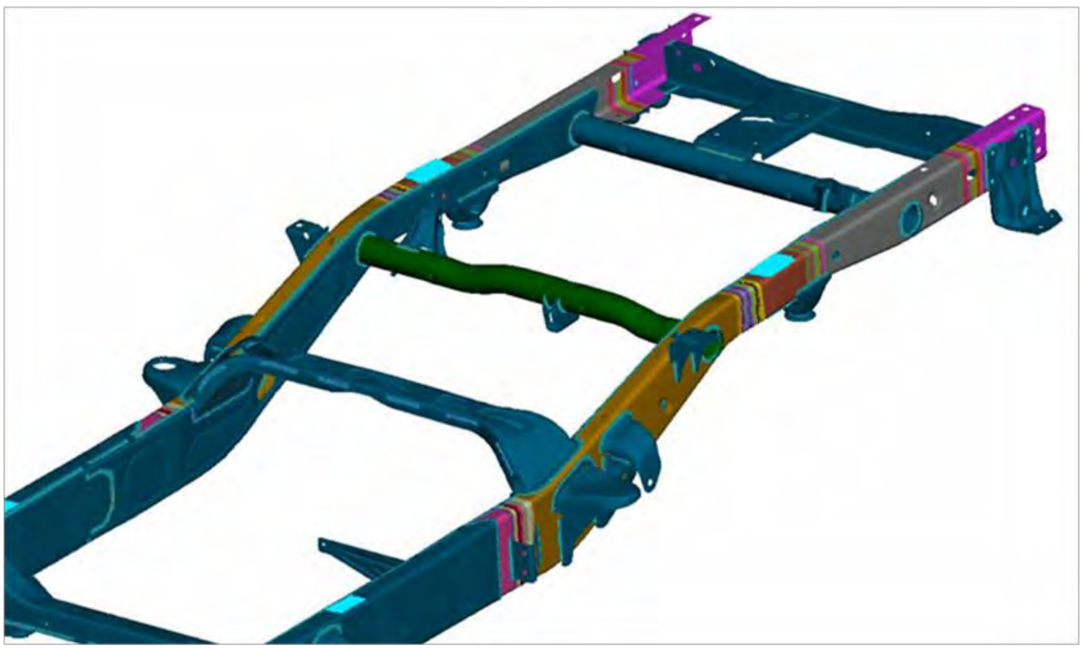

**Figure 2.3-48: Frame Rail Parts Replaced with TRB Parts**
*(Source: EDAG, Inc.)*

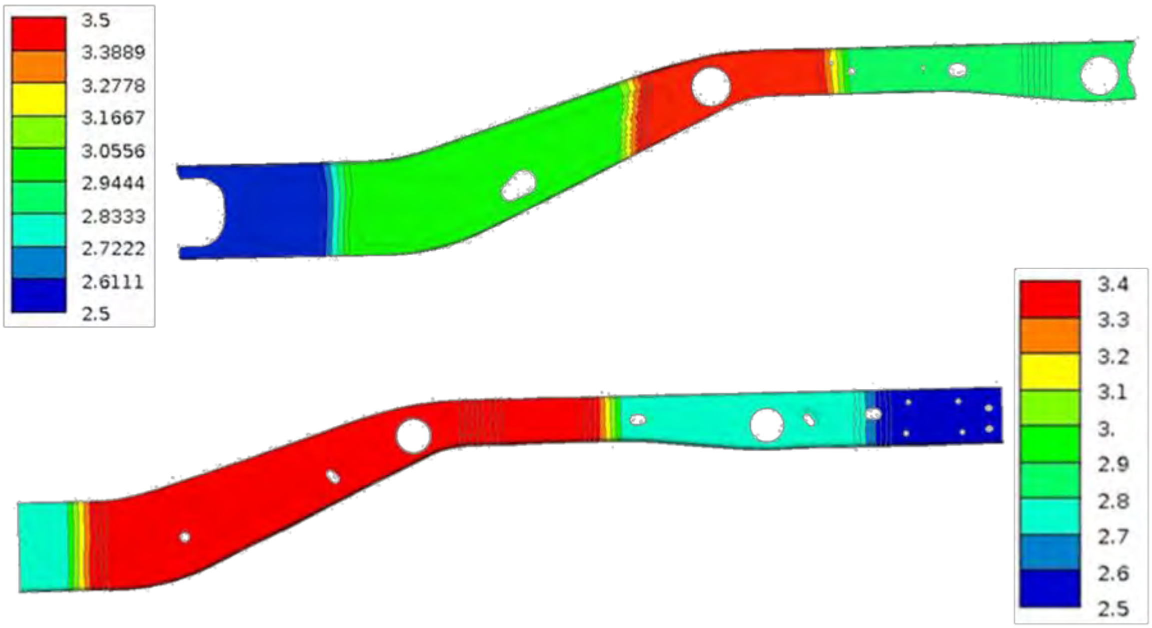


**Figure 2.3-49: Frame Rail TRB Part Gauge Map**
*(Source: EDAG, Inc.)*

It was observed that not all the strategies yielded alternatives in each sub-subsystem. For example, the frame yielded three different alternatives from HSS, aluminum, tailor rolled blank parts, while closures yielded only two alternatives from HSS and aluminum. However reasonable number of alternatives were obtained from each strategy and utilized in the full vehicle optimization.

##### *2.3.2.4.2.5 Subsystem Optimization Results*

Improved and feasible designs were obtained for each subsystem from the above 2GC optimization and subsystem iteration. They are in the form of FE models which are lightweight and within the allowable limits for performance when compared to the baseline subsystems. In addition to the feasible designs, the range of material grades and part thickness were also recorded.

#### 2.3.2.4.3 Full Vehicle Optimization

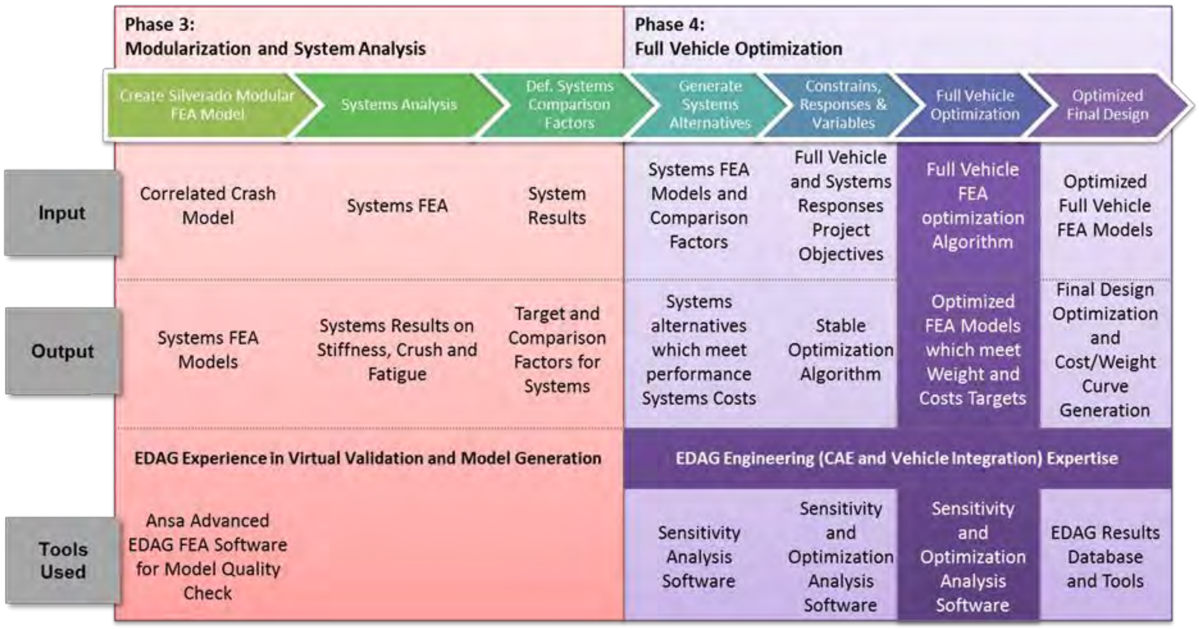


**Figure 2.3-50: Full Vehicle Optimization**

There are two important stages in EDAG's full vehicle optimization process: The first is to evaluate the subsystems for subsystem level tradeoffs; the second is to integrate the adjusted subsystems into full vehicle during the course of full-vehicle optimization. Meeting the full vehicle target performance is still a challenge. Therefore, all the feasible subsystems (alternatives) are included as optimization variables in the full vehicle process. The process of exploring and identifying such feasible subsystems has been explained in the previous Systems Alternatives section.

The full vehicle lightweight design optimization process involved identifying the systems, components, variables, and constraints to be included in the optimization iteration. A load path analysis (as explained in **Section 7.2.4**) was conducted on the baseline model to filter out the parts of higher cross-section forces.

The optimization variables and constraints were defined as per EDAG 3GC optimization guidelines[17, 18]. The variables were gauge (part thickness), grade (material grade), and geometry (part shape). As previously mentioned, geometry change was not included in the optimization; so the entire weight optimization cycle included the following steps:

- Identify subsystems
- Identify components

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17 EDAG CAE Crash and Safety Modeling Guidelines Revision 2.0 Nov 2010

18 EDAG CAE NVH Modeling Guidelines Revision 2.0 Nov 2010

- Select optimization variables including subsystem alternatives
- Setup optimization model
- Perform computer automated optimization
- Extract optimized design variables (response surface)
- Validate optimized results

#### *2.3.2.4.3.1 Gauge and Grade Optimization Model*

A commercially available computerized optimization tool called HEEDS MDO was used to build the optimization model. The model consisted of 408 design variables, eight loadcases (two NVH + six crash), and one cost evaluation. The design variables included 192 gauge variables and 192 grade variables for the identified parts of frame, cabin, and cargo box. The optimization model also included 24 subsystem alternatives (by utilizing HSS/AHSS, aluminum, and TRB). The loadcases selected for optimization were frontal impact with a flat rigid wall barrier, frontal impact with ODB, side impact with MDB, side impact with pole, roof crush, and rear impact. These loadcases were linked in the optimization process in a logical order of structural and crash requirement targets. The optimization tool was setup in such a way as to choose the subsystems iteratively. A typical optimization model built in the HEEDS modeler is shown in **Figure 2.3-40** and **Figure 2.3-51**.

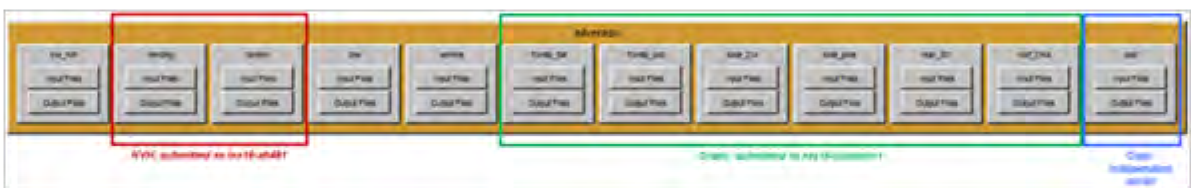


**Figure 2.3-51: Full Vehicle Optimization Model Built in HEEDS**

From **Figure 2.3-51** it can be observed that the full vehicle process includes NVH loadcases as well as crash loadcases, arranged from most critical to less critical in terms of performance metrics. BIW model for NVH loadcase was assembled by selecting the BIW subsystems from the pool of feasible designs. The assembled BIW model was subjected to further gauge changes by the automated algorithm. Similarly, the BIW model for crash loadcases was assembled by selecting the BIW subsystems. The remaining systems and subsystems, i.e., closures, engine, transmission, and other components which are deemed to influence the performance, were then assembled together with the BIW model to build the full vehicle crash model. The crash model was subjected to further grade and gauge changes by the automated algorithm.

The computerized optimization techniques are good choices to achieve any full vehicle trade off analysis in a given time period. It needs shorter range of parameter variations for faster convergence. For this purpose the grade and gauge ranges determined from the subsystem analysis stage were used in the full vehicle optimization. Similarly, the material grades were grouped based on application and manufacturing factors of the parts. **Table 2.3-6** shows material variations in the optimization cycle. Four different material sets were created in such a way that, the grade variation was limited to the assigned sets only.

**Table 2.3-6: Material Grades Variations**

| No. | Material Grade |
|---|---|
| 1 | MILD 140/270 |
| 2 | IF140/270 |
| 3 | BH 210/340 |
| 4 | BH 260/370 |
| 5 | BH 280/400 |
| 6 | DP300/500 |
| 7 | HSLA 350/450 |
| 8 | DP 350/600 |
| 9 | HSLA 420/500 |
| 10 | FB 450/600 |
| 11 | HSLA 490/600 |
| 12 | TWIP 500/980 |
| 13 | DP 500/800 |
| 14 | HSLA 550/650 |
| 15 | SF 570/640 |
| 16 | TRIP 60/980 |
| 17 | DP 700/1000 |
| 18 | CP 800/1000 |
| 19 | MS 950/1200 |
| 20 | CP 1000/1200 |
| 21 | CP 1050/14750 |
| 22 | HF 1050-1500 |
| 23 | MS 1150-1400 |
| 24 | MS 1250-1500 |

Material Set 1 included the materials from 1-11 in Table 2.3-6, Set 2 from 5-14, Set 3 from 10-22 and Set 4 from 16-24. Sets 1 and 2 were assigned for relatively large panel parts, Set 3 was assigned for the critical parts in the load path such as front rail and rear rails, and Set 4 was assigned for B-Pillar and roof rail parts where manufacturing alternatives were preferred.

The number of variables was also reduced by using model symmetry techniques, i.e., symmetrical parts share the same variables. In case of full vehicle examination, CAE analysis time was relatively high when compared to the time taken for the algorithm itself to analyze the results and identify the next step. Therefore, CAE models were run in High-Performance Computing (HPC) systems. The CAE models were distributed in multiple HPC clusters, with NVH and crash loadcase models run in separate HPC systems.

The objective, constraints, and responses considered for this optimization model are found in **Table 2.3-7**.

**Table 2.3-7: Initial Optimization Objective, Response, and Constraints in HEEDs MDO**

| Objective: Minimize Total Weight | | | |
|---|---|---|---|
| **Parameter** | **Requirement** | **Response** | **Constraints/ Target** |
| Bending Stiffness | | Disp. at Shock tower | < 0.36 mm |
| Torsional Stiffness | | Disp. at Rocker | < 0.69 mm |
| Frontal Flat | FMVSS 208 | Max. Pulse | 38 - 41 G |
| | | Dynamic Crush | < 750 mm |
| | | Max. Dash Intrusion | < 100 mm |
| Frontal ODB | IIHS | Max. Pulse | 38 - 41 G |
| | | Dynamic Crush | < 750 mm |
| | | Max. Dash Intrusion | < 150 mm |
| Side 214/IIHS | FMVSS 214 / IIHS | Intrusion Gap | > 125 mm |
| Side Pole | FMVSS 214 Oblique5$^{th}$ | Intrusion Gap | > 125 mm |
| Roof crush | FMVSS 216A | Max. Load | >72,000 N |
| Rear Impact | FMVSS 301 | Zone1 Deformation | < 125 mm |
| | | Zone2 Deformation | < 350 mm |
| Cost | | Total Material Cost | ≤ $ 1200 (+10%) |

**Table 2.3-7 continued next page**

**Table 2.3-7: Initial Optimization Objective, Response, and Constraints in HEEDs MDO cont'd**

| | | | |
|---|---|---|---|
| Side 214/IIHS | FMVSS 214 / IIHS | Intrusion Gap | > 125 mm |
| Side Pole | FMVSS 214 Oblique5th | Intrusion Gap | > 125 mm |
| Roof crush | FMVSS 216A | Max. Load | >72,000 N |
| Rear Impact | FMVSS 301 | Zone1 Deformation | < 125 mm |
| | | Zone2 Deformation | < 350 mm |
| Cost | | Total Material Cost | ≤ $ 1200 (+10%) |

### *2.3.2.4.3.2 Gauge and Grade Optimization Response Surface*

The optimizer was set to 500 design iterations with the objective of minimizing the total weight. The optimizer was checked for convergence of the solution in the course of the optimization cycle. After 13 design cycles (24 designs in the first cycle and 20 designs per subsequent cycles), a response surface of 264 designs was found. The response surface obtained for all the loadcases was investigated to determine the best optimized design. **Figure 2.3-52** shows the response surface output of the optimization cycle for NVH, frontal and side crash loadcases. The remaining loadcases responses have been masked to make the optimized design visible.

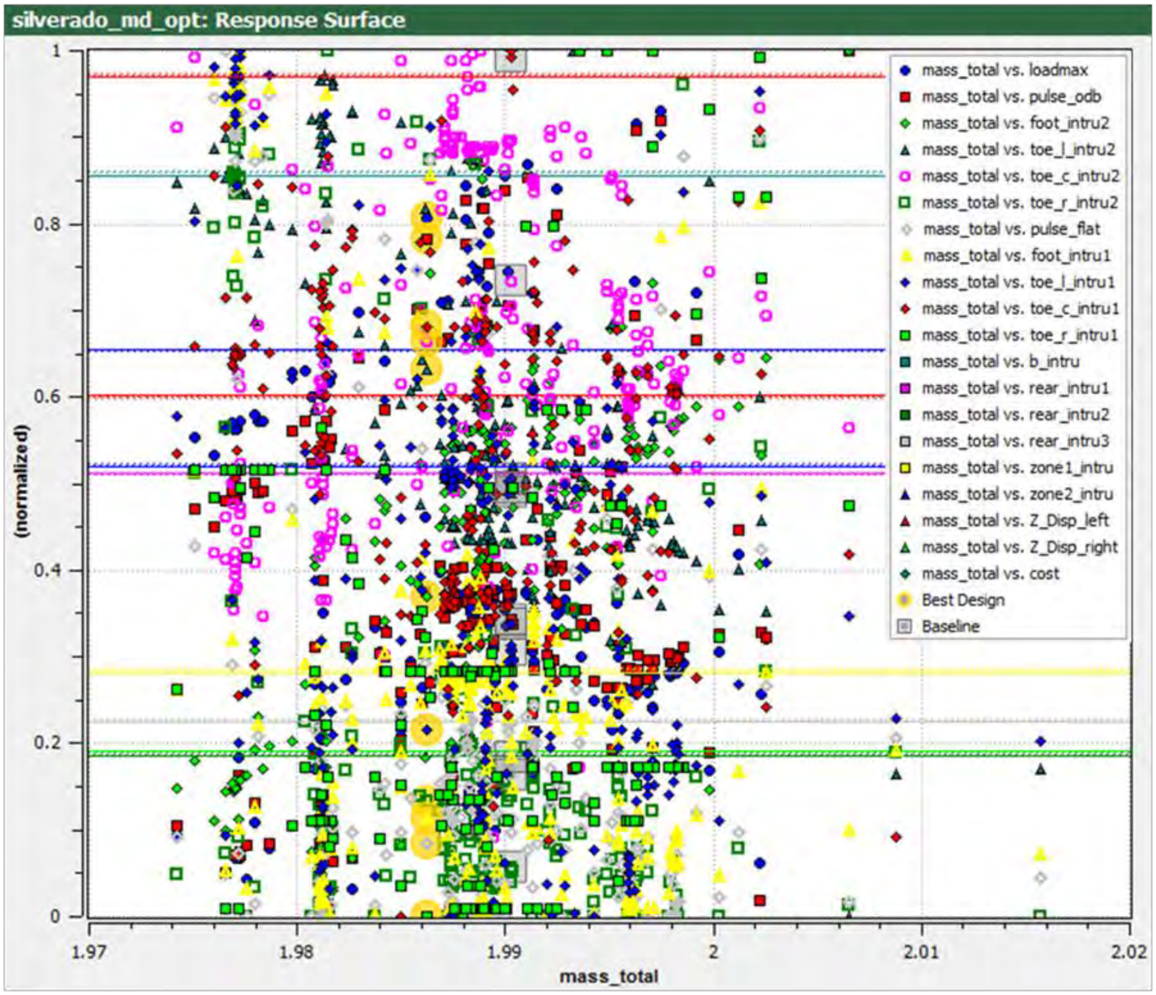



**Figure 2.3-52: Response Surface Output from Optimizer**

### 2.3.2.4.3.3 *Gauge and Grade Optimization Results*

The optimizer returned the optimized set of design variables and the mass optimized NVH and crash models for bending, torsion, frontal impact, frontal ODB, side impact MDB, side impact pole, roof crush resistance, and rear impact models. The responses output by the optimizer, however, were mathematically predicted. As a result, further CAE simulations were performed using the optimized model to confirm the predicted optimum design met the targets.

#### *2.3.2.4.3.4 Human Intelligence*

While the subsystem analysis and full vehicle integrated optimization can be carried out in an automated way using commercially available software, engineering judgment of the external variations of subsystems or components was also a key part of the optimization process. During the execution of evaluation cycles, the CAE model updates were monitored and examined. Any anticipated design changes of the parts influenced by engineering judgment for higher weight reduction potential. The inclusion of new information from the OEMs or the results of other loadcases externally run for verification were updated in the evaluation cycles. It is part of the optimization process that updated iterations (FE model or variables range) were injected as new inputs to the algorithm.

#### *2.3.2.4.3.5 Design and Manufacturing Consideration*

Similar to the subsystem analysis, full vehicle analysis results were further subjected to more weight reduction techniques. The performance levels of the feasible full vehicle models were studied with respect to design and manufacturing feasibilities. Product development expertise, best practices along with engineering judgment could influence the following weight reduction strategies:

- Update the joining technologies
- Update alternative materials options
- Update manufacturing alternatives

Joining: Certain areas of the cabin assembly, converting spot welds to laser welds helped to improve the NVH performance and lead to weight reduction potential.

Material: When the vehicle was investigated in areas where grade and gauge were greatly changed by the analysis, there was still an avenue for weight reduction potential by choosing alternative materials appropriately. The choice of aluminum for the radiator structure not only helped to reduce the weight, but also helped to eliminate multiple sheet metal parts.

Manufacturing: Change of manufacturing techniques was found to be another important weight-reduction option. Hot stamping versus cold stamping, tailored blank versus single-thickness blank are two of commonly used techniques. Taking into consideration the upgrade of the materials and thickness changes of the parts and parts elimination, the manufacturing choices were investigated by iterating the CAE models for all the loadcases. From the cost impact point of view, a balance between cost increase due to manufacturing and weight reduction was monitored as part of this stage of the optimization process. In the case where conventional stamped B-Pillar parts were optimized with hot stamped parts of higher material grade (HF1000/1500), the increase in cost was neutralized by utilizing the TRB parts, which helped to combine the extra B-Pillar inner reinforcements into one B-Pillar inner part, less in assembly cost.

### 2.3.2.4.3.6 *Designs Selection*

The ultimate objective of the optimization process is to obtain an optimized design that is cost effective, light-weight and meets the performance requirements. The set of design evaluations from the full vehicle optimization is analyzed to choose the realistic design. EDAG's approach of selecting the best design from the design evaluations is schematically shown in **Figure 2.3-53**. The green dots depict the feasible designs generated by the optimization tool HEEDS MDO. The area where human intelligence (engineering judgment, best practices and product development expertise) was applied is shown by green box and the area of best designs within this region based on the performance criteria is shown by the blue circle. The final optimized design selected based on the selection criteria is encircled within the area of best designs.

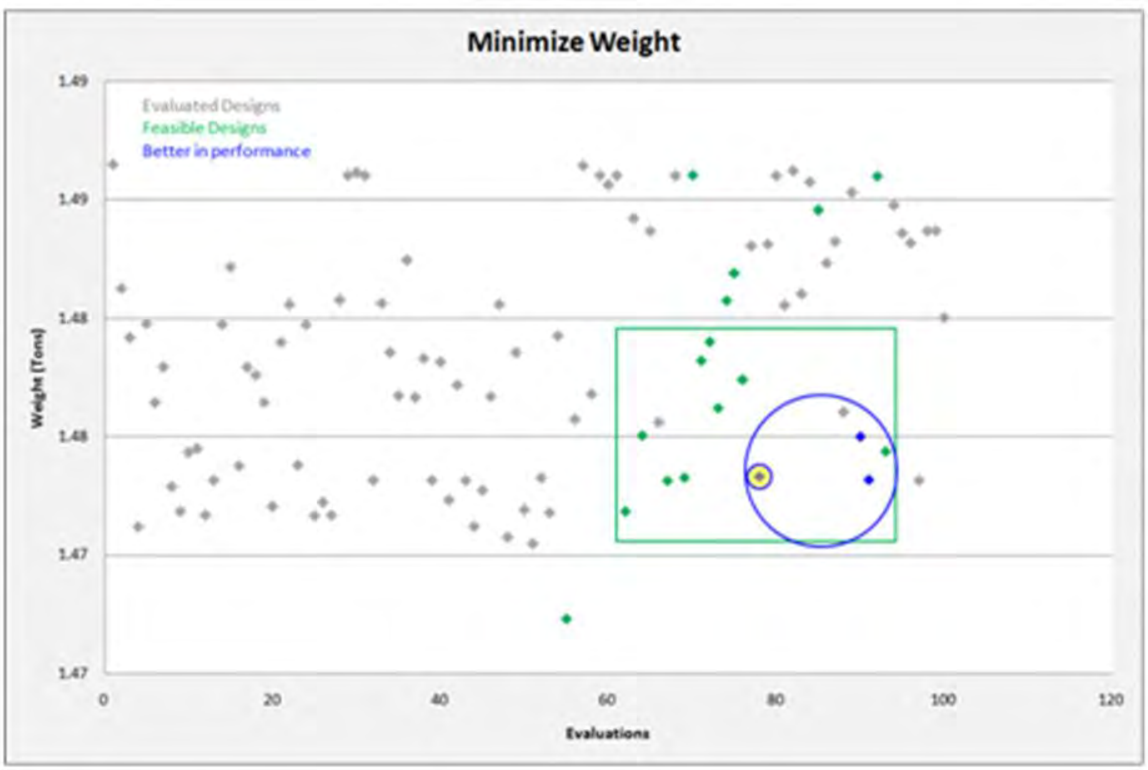



**Figure 2.3-53: Design Selection**

### 2.3.2.4.3.7 *Strategy Analysis*

An important characteristic of this optimization process is the option to extract and analyze data from the evaluation cycles. The results in each stage are one optimized design, and a set of feasible designs including the corresponding parameters such as material grade, gauge, parts shape, weight, and performance metrics. A visual way of analyzing the data is to plot the weight reductions versus the performance and costs.

Therefore, for each weight reduction strategy, the amount of weight opportunity of each subsystem and full vehicle are plotted with respect to its corresponding performance improvement and full vehicle costs. Each weight strategy is analyzed for the performance improvements against the weight opportunity amount with respect to that of the full vehicle. During the course of the optimization, the weight reduction strategies which are consistent with the full vehicle targets are applied on the latest design and injected as new inputs. The weight reductions of several subsystems for each strategy are shown in the plots in the **Appendix Section 7.2.5**.

**Table 2.3-8** and its corresponding scatter plot in **Figure 2.3-54** show the weight reduction and global performance level for each strategy.

**Table 2.3-8: Strategy Analysis**

| No. | Strategy | Full Vehicle | |
|---|---|---|---|
| | | Performance (%) | Weight (kg) |
| 1 (◆) | Baseline | 0.0% | 0.00 |
| 2 (■) | Gauge and Grade | 10.9% | -13.8 |
| 3(▲) | 2 + Eng. Expertise | 9.5% | -59.9 |
| 4 (x) | Gauge Opt | -0.2% | -123.3 |
| 5 (*) | TRB and Laser Weld | 7.5% | -139.0 |
| 6 (●) | DM Feasible | 5.0% | -235.0 |
| 7 (+) | Aluminum/Magnesium | 6.6% | -265.0 |

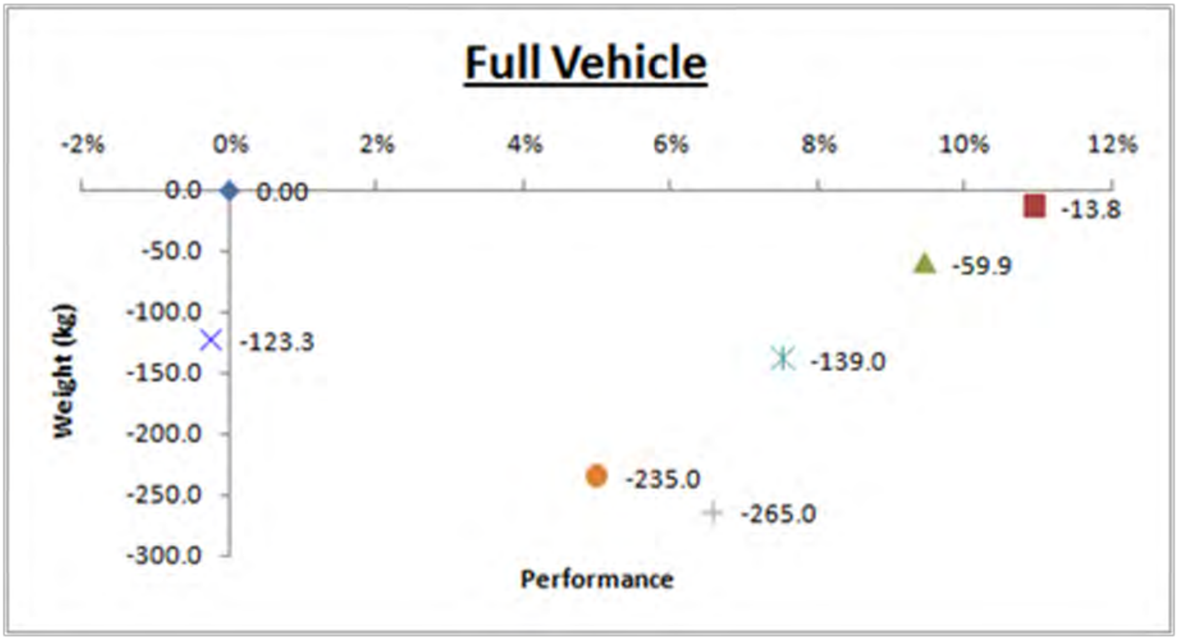



**Figure 2.3-54: Strategy Analysis**

From the preceding illustrations, it can be observed that the gauge-only variation could yield considerable weight reduction, but could also result in the degradation of the vehicle performance. As part of EDAG's best practice for the light weighting process, an initial 5% higher performance target was established and considered a better methodology for the tradeoff process. The choice of gauge only optimization (illustrated as **4(x)**) also might not reveal the full potential of weight reduction as seen by a negative trend in performance. Utilizing material upgrades (mainly steel) in the gauge optimization could greatly improve the performance due to HSS and AHSS characteristics and also lower weight saving (illustrated as **2(■)**). The performance improvement of 10.9% by utilizing HSS and AHSS shows more opportunity to reduce weight. Therefore, the remaining strategies played important roles in the collaborative optimization. Higher weight reductions were achieved systematically stage by stage. Looking at the cost impact in each strategy, the optimized design was selected where the performance target of 5% improvement was met and a near 20% mass reduction achieved.

### *2.3.2.4.3.8 Cost Constraints*

Material cost calculation was always part of the process. Cost was included as key output in both subsystem and full vehicle integrated optimization. In the first two stages (Stage 1 – Subsystem analysis, and Stage 2 – Full vehicle integrated analysis) of the optimization process, the computerized optimization tools were configured with internally developed cost calculation subroutines by using the material grade and gauge change data. In these stages, the manufacturing costs, and assembly cost, were assumed to be same as the baseline and only material cost was used as the constraint. In the next two stages (Stage 3 – Human intelligence, and Stage 4 – Additional weight reduction strategies), the cost impact was included for manufacturing feasibility assessment.

The overall weight reduction opportunities by each strategy with respect to the average cost i.e., cost increase per kilogram weight saving was analyzed. The weight reduction opportunity analysis is illustrated in **Figure 2.3-55**.

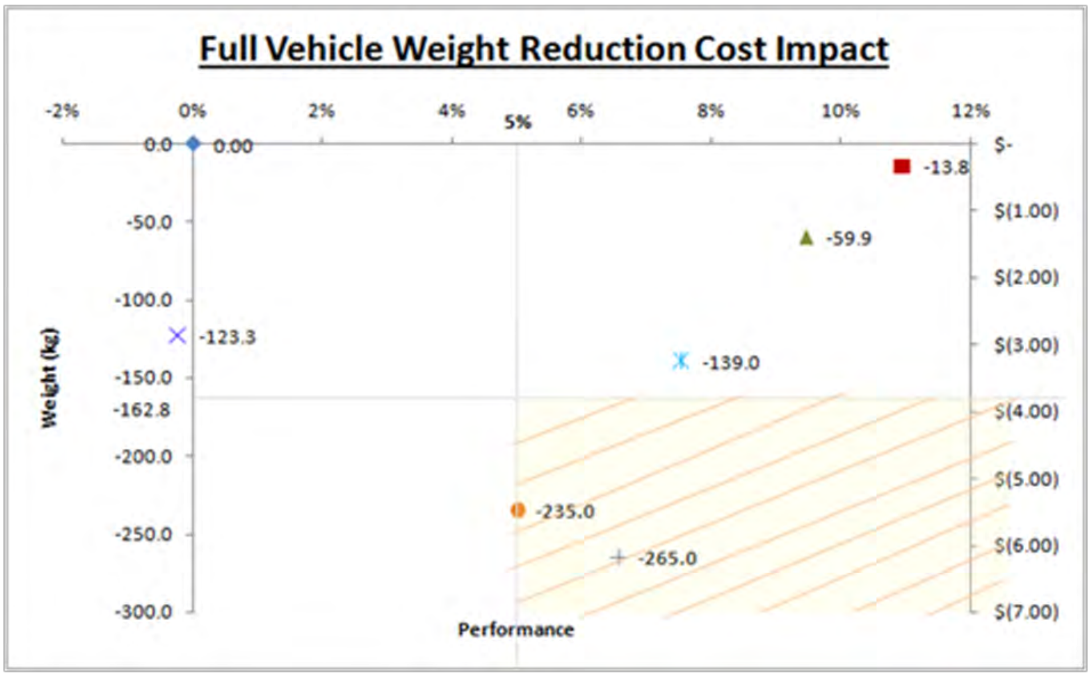



**Figure 2.3-55: Design Selection**

Having a target weight reduction of at least 20% and performance improvement of 5% or higher, the possible light-weight designs are shown in the shaded area. There are two designs found for more than 20% weight reduction and 5% or higher performance targets. Out of these two designs, the one with the lower cost/kg, (235 kg savings) is selected as the optimized final design. Additional details on the EDAG costing methodology are found in **Section 2.4.2**, **Body and Frame Evaluation Group – Cost Modeling Details**.

## 2.4 Cost Modeling Details

The costs developed in this analysis are referred to as Net Incremental Direct Manufacturing Costs (NIDMCs). The NIDMCs are the incremental differences in cost of components and assembly to the OEM, between the mass-reduced technology configuration and the baseline technology configuration. This includes both external costs, for purchased components and assemblies from suppliers, as well as internal costs for manufacturing operations performed by the OEM.

The cost elements included in a standard NIDMC model are broken out into three categories (**Figure 2.4-1**). Total Manufacturing Cost (TMC) includes material, labor and manufacturing overhead cost contributions. The mark-up costs include end-item scrap expenses, selling, general and administrative (SG&A) expenses, profit, and engineering, design, and testing (ED&T) expenses. The final category is packaging costs.

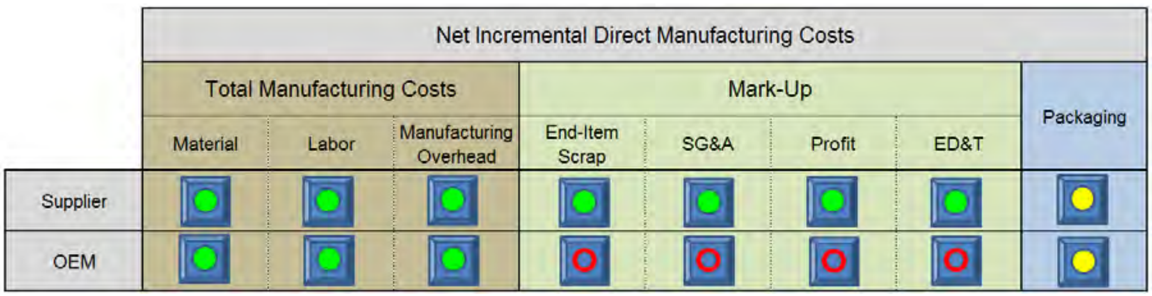



**Figure 2.4-1: Net Incremental Direct Manufacturing Cost Elements**

For the purpose of this mass reduction analysis, component/assembly packaging costs were considered to be neutral due to the relative size envelope of these parts not changing significantly between the production stock and mass-reduced parts.

The cost models for both the supplier and OEM manufactured components, assemblies and systems, included material, labor and manufacturing overhead cost contributions. In the supplier manufactured components/assemblies, mark-up was also accounted for in the NIDMC models. However in the OEM NIDMC models, mark-up contributions were not included. This has been standard protocol for all costing studies conducted by FEV for the EPA. The OEM mark-up/indirect manufacturing costs are accounted for by applying an indirect cost multiplier (ICM) to the final summation of NIDMCs. The product of NIDMCs, and applicable ICMs, equals the incremental cost of the new technology to the end consumer under the assumed project boundary conditions.

When differences in the boundary conditions are considered, additional adjustments to the NIDMCs are required. For EPA studies this is accomplished with the application of Learning/Experience Factors (LFs). In this analysis, only supplier and OEM NIDMCs are calculated. The application of ICMs and LFs are outside the project scope (**Figure 2.4-2**). Additional details on the application of ICMs and Learning Factors can be found in the EPA and NHTSA Joint Final Rule, “2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards.”

$$\text{Incremental Cost To End Consumer for Vehicle Mass Reduction} = \underbrace{\left[\sum \text{Supplier NIDMC ( TMC + Markup + Packaging)} + \sum \text{OEM NIDMC ( TMC + Packaging )}\right]}_{\text{Within Project Scope}} \underbrace{\times \text{ ICM } \times \text{ LF}}_{\text{Outside Project Scope}}$$

**Figure 2.4-2: Mass Reductions Costs Included in the Analysis**

The remainder of Section 2.4 covers additional details on the cost modeling portion of the analysis. The same general costing methodology and assumptions were applicable to all vehicle systems evaluated; however, the costing tools differed between the Powertrain, Chassis, and Trim Evaluation Group and the Body and Frame Costing Group.

For the Powertrain, Chassis, and Trim Evaluation Group, costing tools developed by FEV and Munro were utilized. These were the same tools used in the Midsize CUV report (EPA Report #: EPA-420-R-12-026, "Light-Duty Vehicle Mass Reduction and Cost Analysis-Midsize Crossover Utility Vehicle") as well as numerous other advance light-duty powertrain technology cost assessments recently completed for both government and commercial institutions. For the Body and Frame Evaluation Group, incremental costs were estimated using the Technical Cost Modeling (TCM) approach developed by the Massachusetts Institute of Technology (MIT). EDAG had employed these same tools in the Venza mass reduction and cost assessment, and in prior studies including the Future Steel Vehicle Phase 1 and Phase 2 analyses. As part, the Venza mass reduction and cost analysis project, the two cost modeling approaches were checked using several BIW component examples to ensure there was good correlation between the results using the two different costing tools. The two report sections that follow discuss the Powertrain, Chassis, and Trim Evaluation Group – Cost Modeling Details (**Section 2.4.1**), and the Body and Frame Evaluation Group - Costing Modeling Details (**Section 2.4.2**).

### 2.4.1 Powertrain, Chassis and Trim Evaluation – Cost Modeling Details

The costing methodology used to support the Powertrain, Chassis, and Trim evaluation group consisted of four main process steps, as illustrated in **Figure 2.4-3**. **Step 1** defined the cost analysis boundary conditions. The boundary conditions are critical for establishing a consistent framework for comparison, ensuring all vehicle systems for both the current production technology as well as the mass-reduced technology are costed with the same assumptions (e.g., volume, manufacturing location, mark-up rates, manufacturing cost structures).

**Step 2** involved updating the databases and process parameter models based on the established analysis boundary conditions. In addition new materials and processes may have been identified in the initial teardowns and idea generation stages, which do not currently exist in the current databases or process parameter libraries. Before costing modeling is initiated, database and process parameter model updates are made based on the initial assessment. Further database and process parameter model updates are made during the cost modeling process as required.

The cost analysis begins in **Step 3**. Based on the type of components under evaluation, the vehicle system team lead determines if commodity costing or detail costing is required for each component. Commodity costing is generally reserved for low-impact type components and/or components for which pricing exists in a commodity database of similar components based on prior cost studies or acquired quotes. Generally, commodity-type costing is reserved for fastening hardware (nuts, bolts, washers, seals, etc.) and mass-produced, lower dollar value, mature components. Examples of these types of components include standard pressure or temperature sensors, spark plugs, small wire harnesses, suspension bushings, and isolators. Custom vehicle specific components and/or moderate- to high-impact type components are costed using detailed cost models. The internal steps involved in acquiring and validating commodity and detailed costs are shown in **Figure 2.4-3**.

As component costs are developed, they are summed into cost model analysis templates (CMATs) at the assembly/sub-subsystem, subsystem, and system level. For example, the cost impact of light-weighting a connecting rod can be found in a connecting rod assembly/sub-subsystem CMAT (010303 Connecting Rod SSSCMAT). The net cost impact of the connecting rod and other light-weighted crank drive components (e.g., piston, crankshaft, flywheel) can be found in a Crank Drive Subsystem CMAT (0103 Crank Drive Subsystem SSCMAT). Finally, the net cost impact of the Crank Drive Subsystem and other engine subsystems (e.g., Cylinder Block, Cylinder Head, Timing Drive) can be found in an Engine System CMAT (01 Engine SCMAT). The final step entails rolling up the mass reduction net cost impact for each vehicle system into a vehicle level CMAT (Silverado VCMAT).

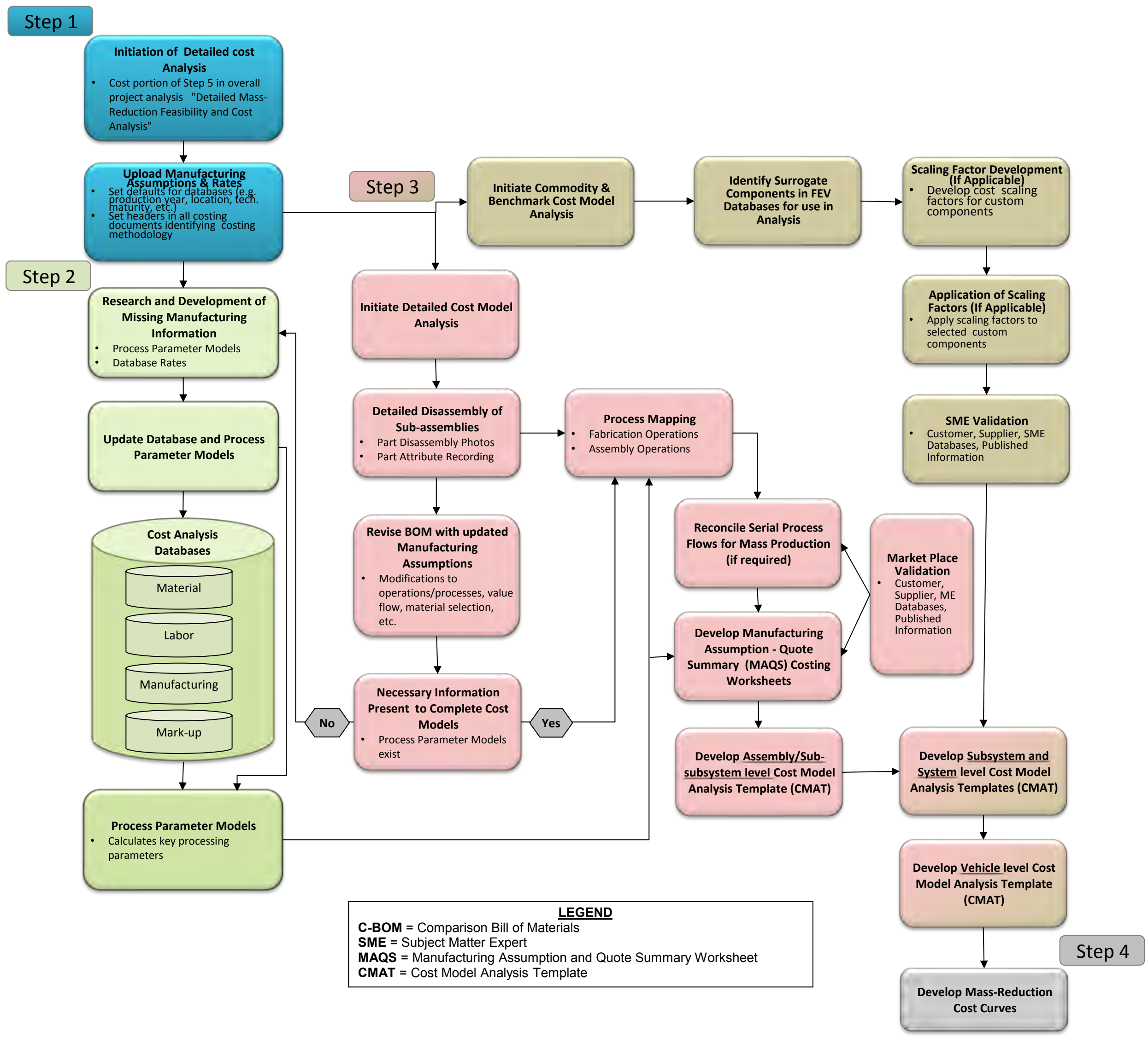



**Figure 2.4-3: Cost Methodology Steps for Powertrain, Chassis and Trim Evaluation Group**

In the final step, **Step 4**, developed costs are plotted from best to least value in terms of costs per kilogram of mass reduction. The objective of which was to determine the average cost per kilogram of mass reduction at various levels of vehicle mass reduction up through 20%. A secondary objective was to evaluate the benefit of secondary mass-savings relative to average cost per kilogram for mass reduction.

In the sections which follow, additional details are provided on the four steps relative to methodology and tools utilized.

#### 2.4.1.1 Step 1: Costing Boundary Conditions

For both the baseline Chevrolet Silverado components and the new mass-reduced replacement components the same universal set of boundary conditions are utilized in order to establish a constant framework for all costing. The primary assumption is that the OEM and suppliers have the option of tooling up either the baseline components (i.e., production stock Silverado components) or the mass-reduced components. The same product maturity levels, manufacturing cost structure (e.g., production volume, manufacturing location, and manufacturing period), and market conditions exist for both technologies. This common framework for costing permits reliable comparison of costs between new mass-reduced components and baseline production stock Chevrolet Silverado components. In addition, having a good understanding of the analysis boundary conditions (i.e., what assumptions made in the analysis, the methodology utilized, what parameters included in the final numbers, etc.), a fair and meaningful comparison can be made between results developed from alternative costing methodologies and/or sources. **Table 2.4-1** captures the primary universal cost analysis assumptions which are applicable to both the new and baseline configurations evaluated in the analysis. The assumptions are applicable to the vehicle systems included in the Powertrain, Chassis, and Trim as well as the Body and Frame Evaluation Groups.

## Table 2.4-1: Universal Case Study Assumption Utilized in the Mass Reduction Analysis

| Item | Description | Universal Case Study Assumptions |
|---|---|---|
| 1 | Net Incremental **Direct** Manufacturing Costs (NIDMC)<br>(Included in the analysis) | A.Net Incremental **Direct** manufacturing cost is the incremental difference in cost of components and assembly, to the OEM, between the new technology configuration (i.e., mass-reduced components/assemblies) and the baseline technology configuration (i.e., the production stock Chevrolet Silverado components/assemblies).<br><br>B. This value does not include **Indirect** OEM costs associated with adopting the new technology configuration (e.g. tooling, corporate overhead, corporate R&D, etc.). |
| 2 | Incremental **Indirect** OEM Costs<br>(Not included within the scope of this cost analysis) | A. Indirect Costs are handled through the application of "**Indirect Cost Multipliers**" (ICMs) which are not included as part of this analysis. The ICM covers items such as .....<br>a. OEM corporate overhead (sales, marketing, warranty, etc.)<br>b. OEM engineering, design and testing costs (internal & external)<br>c. OEM owned tooling<br><br>B. Reference EPA report EPA-420-R-09-003, February 2009, "Automobile Industry Retail Price Equivalent and Indirect Cost Multiplier" for additional details on the develop and application of ICM factors.<br><br>C. Reference EPA and NHTSA Joint Final Rule "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards", Federal Register / Vol. 77, No. 199 / Monday, October 15, 2012 / Rules and Regulations (http://www.gpo.gov/fdsys/pkg/FR-2012-10-15/pdf/2012-21972.pdf) for additional details on the develop and application of ICM and learning factors. |
| 3 | Incremental Production Tooling Costs<br>(Included in the analysis) | A. Incremental Production Tooling cost is the differential cost of tooling to the OEM, between tooling up the new technology configuration (i.e., mass-reduced components/assemblies) versus the baseline technology configuration (i.e., the production stock Silverado components/assemblies).<br><br>B. Analysis assumes all tooling is owed by OEM<br><br>C. Tooling includes items like stamping dies, plastic injection mold, die casting molds, weld fixtures, assembly fixtures, gauges, etc. |
| 4 | Product/Technology Maturity Level | A. Mature technology assumption, as defined within this analysis, includes the following:<br>a. Well developed product design<br>b. High production volume (+450K/year)<br>c. Products in service for several years at high volumes<br>c. Significant market place competition<br><br>B. Mature Technology assumption establishes a consistent framework for costing. For example, a defined range of acceptable mark-up rates.<br>a. End-item-scrap 0.3-0.7%<br>b. SG&A/Corporate Overhead 6-7%<br>c. Profit 4-8%<br>d. ED&T (Engineering, Design and Testing) 0-6%<br><br>C. The technology maturity assumption does not include allowances for product learning. Application of a **learning curve** to the calculated incremental direct manufacturing cost is handled outside the scope of this analysis. |

**Table 2.4-1 continued next page**

**Table 2.4-1: (Cont'd) Universal Case Study Assumption Utilized in the Mass Reduction Analysis**

| Item | Description | Universal Case Study Assumptions |
|---|---|---|
| 5 | Selected Manufacturing Processes and Operations | A. All operations and processes are based on existing standard/mainstream Industrial practices.<br><br>B. No additional allowance is included in the incremental direct manufacturing cost for manufacturing learning. Application of a **learning curve** to the developed incremental direct manufacturing cost is handled outside the scope of this analysis. |
| 6 | Annual Capacity Planning Volume | 450,000 Vehicles |
| 7 | Supplier Manufacturing Location | United States of America |
| 8 | OEM Manufacturing Location | United States of America |
| 9 | Manufacturing Cost Structure Timeframe ( e.g. Material Costs, Labor Rates, Manufacturing Overhead Rates) | 2012/2013 Production Year Rates |
| 10 | Packaging Costs | A. Calculated on all Tier One (T1) supplier level components.<br><br>B. For Tier 2/3 (T2/T3) supplier level components, packaging costs are included in T1 mark-up of incoming T2/T3 incoming goods. |
| 11 | Shipping and Handling | A. T1 supplier shipping costs covered through application of the Indirect Cost Multiplier (ICM) discussed above.<br><br>B. T2/T3 to T1 supplier shipping costs are accounted for via T1 mark-up on incoming T2/T3 goods. |
| 12 | Intellectual Property (IP) Cost Considerations | Where applicable IP costs are included in the analysis. Based on the assumption that the technology has reached maturity, sufficient competition would exist suggesting alternative design paths to achieve similar function and performance metrics would be available minimizing any IP cost penalty. |
| 13 | Platform Synergies Considerations | No consideration was given (positive or negative ) to x-platform synergies. Both the baseline and mass-reduced technology configurations were treated the same.<br>a. Common parts used across different models<br>b. Parts homologated / validated / certified for various worldwide markets |
| 14 | Derivative Model Considerations | No consideration was given to derivative models. Both the baseline and mass-reduced technology configurations were treated the same.<br>a. 2 wheel, 4 wheel or all wheel drive applications<br>b. Various engine / transmission options with models<br>c. Various towing / loading / carrying capacities |
| 15 | Material Cost Reductions (MCRs) on analyzed hardware | Only incorporated on those components where it was evident that the component design and/or selected manufacturing process was chosen due to actual low production volumes (e.g. design choice made to accept high piece price to minimize tooling expense). Under this scenario, assumptions where made, and cost analyzed assuming high production volumes. |
| 16 | Operating and End-of Life Costs | No new, or modified, maintenance or end-of-life costs, were identified in the analysis. |
| 17 | Stranded Capital or ED&T expenses | No stranded capital or non-recovered ED&T expenses were considered within the scope of this analysis. It was assumed the integration of new technology would be planned and phased in minimizing non-recoverable expenses. |

### 2.4.1.2 Step 2: Databases and Process Parameter Models

**Figure 2.4.1** highlights the three main cost element categories that make up the NIDMCs for all components and assemblies in the analysis. Every cost element used throughout the analysis is extracted from one of the core databases. There are the databases for material prices ($/kilogram), labor rates ($/hour), manufacturing overhead rates ($/hour), mark-up rates (% of TMC), and packaging ($/packaging option). The databases provide the foundation of the cost analysis, since all costs originate from them. They are also used to document sources and supporting information for the cost numbers.

The model allows for updates to the cost elements, which automatically roll into the individual component/assembly cost models. Since all cost sheets and parameters are directly linked to the databases, changing any of the "Active Rate" cost elements in the applicable database automatically updates the cost model worksheets [i.e., Manufacturing Assumption Quote Summary (MAQS) worksheets]. Thus, if a material doubles in price, one can easily assess the impact on the technology configurations under study.

#### 2.4.1.2.1 Material Database

The Material Database houses specific material prices and related material information required for component cost estimating analysis. The information related to each material listed includes the material name, standard industry identification (e.g., AISI or SAE nomenclature), typical automotive applications, pricing per kilogram, annual consumption rates, and source references. The prices recorded in the database are in U.S. dollars per kilogram.

**Material Selection Process**

The materials listed in the database (resins, ferrous, and non-ferrous alloys) are used in the products and components selected for cost analysis. The materials identification process was based on visual part markings, part appearance, manufacturing method, and part application. Material markings are the most obvious method of material identification. Resin components typically have material markings (e.g., >PA66 30GF<) which were easily identified, recorded in the database, and researched to establish price trends.

For components which were not marked, such as transmission gears, suspension knuckles, engine connecting rods, and the like, the FEV and Munro cross-functional team members and contracted subject matter experts (SME) were consulted in the materials identification. For any material still not identified, information published in print and on the web was researched, or primary manufacturers and experts within the Tier 1 supplier community were contacted to establish credible material choices.

The specific application and the part appearance play a role in materials identification. Steels commonly referred to as work-hardenable steels with high manganese content (13% Mn) are readily made in a casting and are not forgeable. Therefore, establishing whether a component is forged or casted can narrow the materials identification process. Observing visual cues on components can be very informative. Complex part geometry alone can rule out the possibility of forgings; however, more subtle differences must be considered. For example, forged components typically have a smoother appearance in the grain whereas cast components have a rougher finish, especially in the areas where machining is absent. Castings also usually display evidence of casting flash.

The component application environment will also help determine material choice. There are, for example, several conventional ductile cast iron applications found in base gasoline engines that are moving to high silicon-molybdenum ductile or Ductile Ni-Resist cast irons in downsized turbocharged engines. This is due to high temperature, thermal cycling, and corrosion resistance demands associated with elevated exhaust gas temperatures in turbocharged engines. Therefore, understanding the part application and use environment can greatly assist in achieving more accurate material determinations.

**Pricing Sources and Considerations**

The pricing data housed in the database was derived from various sources of publicly available data from which historical trend data could be derived. The objective was to find historical pricing data over as many years as possible to obtain the most accurate trend response. Ferrous and non-ferrous alloy pricing involved Internet searches of several sources, including the U.S. Geological Survey (USGS), MEPS (previously Management Engineering & Production Services), Metal-Pages, London Metal Exchange, estainlesssteel.com, and Longbow.

Resin pricing was also obtained from sources such as Plastics News, Plastics Technology Online, Rubber and Plastics News, and IDES (Integrated Design Engineering Systems). Several other sources are used in this research as outlined in the database.

Though material prices are often published for standard materials, prices for specialized material formulations and/or those having a nonstandard geometric configuration (e.g., length, width, thickness, cross-section) are not typically available. Where pricing is not available for a given material with a known composition, two approaches were used: industry consultation and composition analysis.

Industry consultation mainly takes the form of discussions with subject matter experts familiar with the material selection and pricing used in the products under evaluation to acquiring formal quotes from raw material suppliers.

In those cases where published pricing data was unavailable and raw material supplier quotes could not be acquired, a composition analysis was used. This was achieved by building prices based on element composition and applying a processing factor (i.e., market price/material composition cost) derived from a material within the same material family. The calculated price was compared to other materials in the same family as a means to ensure the calculated material price was directionally correct.

Obtaining prices for unknown proprietary material compositions, such as powder metals, necessitated a standardized industry approach. In these cases, manufacturers and industry market research firms are consulted to provide generic pricing formulas and pricing trends. Their price formulas are balanced against published market trends of similar materials to establish new pricing trends.

Resin formulations are also available with a variety of fillers and filler content. Some pricing data is available for specific formulations; however, pricing is not published for every variation. This variation is significant since many manufacturers can easily tailor resin filler type and content to serve the specific application. Consequently the database has been structured to group resins, with common filler, into ranges of filler content. For example, glass-filled Nylon 6 is grouped into three categories: 0% to 15% glass-filled, 30% to 35% glass-filled, and 50% glass-filled, each with their own price point. These groupings provide a single price point as the price differential within a group (0% to 15% glass-filled) is not statistically significant.

**In-process Scrap**

In-process scrap is defined as the raw material mass, beyond the final part weight, required to manufacture a component. For example, in an injection molded part, the in-process scrap is typically created from the delivery system of the molten plastic into the part cavity (e.g., sprue, runners and part gate). This additional material is trimmed off following part injection from the mold. In some cases, dependent on the material and application, a portion of this material can be ground up and returned into the virgin material mix.

In the case of screw machine parts, the in-process scrap is defined as the amount of material removed from the raw bar stock in the process of creating the part features. Generally, material removed during the various machining processes is sold at scrap value. Within this cost analysis study, no considerations were made to account for recovering scrap costs with the excpetion of wrough aluminum and magnesium.

A second scrap parameter accounted for in the cost analysis is end-item scrap. End-item scrap is captured as a cost element within mark-up and will be discussed in more detail within the mark-up database section. Although, it is worth reiterating here that in-process scrap only covers the additional raw material mass required for manufacturing a part, it does not include an allowance for quality defects, rework costs and/or destructive test parts. These costs are covered by the end-item scrap allowance.

**Purchase Parts – Commodity Parts**

Many of the parts considered to be purchased are simple standard fasteners (nuts, bolts, screws, washers, clips, hose clamps) and seals (gaskets, O-rings). However, in certain cases, more value-added components are considered purchased when sufficient data existed supporting their cost as a commodity: that is, where competitive or other forces drive these costs to levels on the order of those expected had these parts been analyzed using the detailed cost models.

In the MAQS worksheet, standard purchase parts costs are binned to material costs, which, in the scope of this analysis, are generally understood to be raw material costs. If the purchase part content for a particular assembly or system is high in dollar value, the calculated cost breakdown in the relevant elements (i.e., material, labor, manufacturing overhead, mark-up) tended to be misleading. That is the material content would show artificially inflated because of the high dollar value of purchase part content.

To try and minimize this cost binning error, purchase parts with a value in the range of $10 to $15, or greater, were broken into the standard cost elements using cost element ratios developed for surrogate type parts. For example, assume a detailed cost analysis is conducted on a roller bearing assembly, "Bearing A." The ratio of material, labor, manufacturing overhead, and mark-up, as a percent of the selling price, can easily be calculated. Knowing the commodity selling price for a similar type of bearing assembly, "Bearing B," along with the cost element ratios developed for "Bearing A," estimates can be made on the material, labor, manufacturing overhead, and mark-up costs for "Bearing B."

Purchased part costs are obtained from a variety of sources. These include FEV and Munro team members' industry cost knowledge and experience, surrogate component costing databases, Tier 1 supplier networks, published information, and service part cost information.

2.4.1.2.2 <u>Labor Database</u>

The Labor Database contains all the standard occupations and associated labor rates required to manufacture automotive parts and vehicles. All labor rates referenced throughout the cost analysis are referenced from the established Labor Database.

Hourly wage rate data used throughout the study, with exception of fringe and wage projection parameters, is acquired from the Bureau of Labor Statistics (BLS). For the analysis, mean hourly wage rates were chosen for each occupation, representing an average wage across the United States.

The Labor Database is broken into two primary industry sections, Motor Vehicle Parts Manufacturing (supplier base) and Motor Vehicle Manufacturing (OEMs). These two industry sections correspond to the BLS, North American Industry Classification System

(NAICS) 336300 and 336100 respectively. Within each industry section of the database, there is a list of standard production occupations taken from the BLS Standard Occupation Classification (SOC) system. For reference, the base SOC code for production occupations within the Motor Vehicle Parts Manufacturing and Motor Vehicle Manufacturing is 51-0000. Every production occupation listed in the Labor Database has a calculated labor rate, as discussed in more detail below. For the Chevrolet Silverado mass reduction and cost analysis study, 2012 rates were used (2012 rates published in May 2013).

**Direct Versus Total Labor, Wage Versus Rate**

Each standard production occupation found in the Labor Database has an SOC identification number, title, labor description, and mean hourly wage taken directly from the BLS.

Only "direct" production occupations are listed in the labor database. Team assemblers and forging, cutting, punching, and press machine operators are all considered direct production occupations. There are several tiers of manufacturing personnel supporting the direct laborers that need to be accounted for in the total labor costs, such as quality technicians, process engineers, lift truck drivers, millwrights, and electricians. A method typically used by the automotive industry to account for all of these additional "indirect labor" costs – and the one chosen for this cost analysis – is to calculate the contribution of indirect labor as an average percent of direct labor, for a given production occupation, in a given industry sector.

The BLS Database provides labor wage data, rather than labor rate data. In addition to what a direct laborer is paid, there are several additional expenses the employer must cover in addition to the employee base wage. This analysis refers to these added employer expenditures as "fringe." Fringe is applicable to all employees and will be discussed in greater detail following.

It should be noted that the BLS motor vehicle and motor vehicle parts manufacturing (NAICS 336100 & 336300) labor rates include union and non-union labor rates, reflecting the relative mix of each in the workforce at the time the data was gathered (2012).

**Contributors to Labor Rate and Labor Rate Equation**

The four contributors to labor costs used in this study are:

**Direct Labor** (DIR) is the ***mean*** manufacturing labor wage directly associated with fabricating, finishing, and/or assembling a physical component or assembly. Examples falling into this labor classification include injection mold press operators, die cast press operators, heat treat equipment operators, team/general assemblers, computer numerical controlled (CNC) machine operators, and stamping press operators. The median labor wage for each direct labor title is also included in the database. These values are treated as reference only.

**Indirect Labor** (IND) is the manufacturing labor indirectly associated with making a physical component or assembly. Examples include material handling personnel, shipping and receiving personnel, quality control technicians, first-line supervisors, and manufacturing/process engineers. For a selected industry sector (such as injection molding, permanent casting, or metal stamping), an average ratio of indirect to direct labor costs can be derived from which the contribution of indirect labor ($/hour) can be calculated.

This ratio is calculated as follows:

1. An industry sector is chosen from the BLS, NAIC System. (e.g., Plastics Product Manufacturing NAICS 326100).
2. Within the selected industry sector, occupations are sorted (using SOC codes) into one of the four categories: Direct Labor, Indirect Labor, MRO Labor, or Other.
3. For each category (excluding "Other") a total cost/hour is calculated by summing up the population weighted cost per hour rates, for the SOC codes within each labor category.
4. Dividing the total indirect labor costs by total direct labor costs, the industry sector ratio is calculated.
5. When multiple industries employ the same type direct laborer, as defined by NAICS, a weighted average of indirect to direct is calculated using the top three industries.

**Maintenance Repair and Other** (MRO) is the labor required to repair and maintain manufacturing equipment and tools ***directly*** associated with manufacturing a given component or assembly. Examples falling into this labor classification include electricians, pipe fitters, millwrights, and on-site tool and die tradesmen. Similar to indirect labor, an average ratio of MRO to direct labor costs can be derived from which the contribution of MRO labor ($/hour) can be calculated. The same process used to calculate the indirect labor ratio is also used for the MRO ratio.

**Fringe** (FR) is all the additional expenses a company must pay for an employee above and beyond base wage. Examples of expenses captured as part of fringe include company medical and insurance benefits, pension/retirement benefits, government directed benefits, vacation and holiday benefits, shift premiums, and training.

Fringe applies to all manufacturing employees. Therefore the contribution of fringe to the overall labor rate is based on a percentage of direct, indirect and MRO labor. Two fringe rates are used: 52% for supplier manufacturing, and 160% for OEM manufacturing. The supplier manufacturing fringe rate is based on data acquired from the BLS (Table 21: Private Industry workers, full-time by industry group: employer costs per hours worked for employee compensation and costs as a percentage of total compensation, 2004-2012). Taking an average of the "Total Compensation" divided by "Wages and Salaries" for manufacturing years 2008 through 2012, an average fringe rate of 52% was calculated.

Due to the dynamic change of OEM wage and benefit packages over the last few years (2008-2012), and differences among the OEMs, no updates were made from the original OEM fringe assumptions developed for the initial "Light-Duty Technology Cost Analysis Pilot Study" EPA-420-R-09-020 (http://www.epa.gov/OMS/climate/420r09020.pdf). The OEM fringe rate utilized throughout the analysis was 160%.

#### 2.4.1.2.3 Manufacturing Overhead Database

The Manufacturing Overhead Database contains several manufacturing overhead rates (also sometimes referred to as "burden rates," or simply as "burden") associated with various types of manufacturing equipment that are required to manufacture automotive parts and vehicles. Combined with material and labor costs, it creates the total manufacturing cost (TMC) to manufacture a component or assembly. Manufacturing equipment is typically one of the largest contributors to manufacturing overhead, so manufacturing overhead rates are categorized according to primary manufacturing processes and the associated equipment as:

1. The first tier of the Manufacturing Overhead Database is arranged by the primary manufacturing process groups (e.g., thermoplastic molding, thermoset molding, castings, forgings, stamping and forming, powder metal, machining, turning).
2. The second tier subdivides the primary manufacturing process groups into primary processing equipment groups. For example the 'turning group' consists of several subgroups including some of the following: (1) CNC turning, auto bar fed, dual axis machining, (2) CNC turning, auto bar fed, quad axis machining, (3) CNC turning, auto bar fed, dual axis machining, double-sided part, and (4) CNC turning, auto bar fed, quad axis machining, double-sided part.
3. The third and final tier of the database increases the resolution of the primary processing equipment groups and defines the applicable manufacturing overhead rates. For example, within the "CNC turning, auto bar fed, dual axis machining" primary process equipment group, there are four available machines sizes (based on maximum cutting diameter and part length) from which to choose. The added resolution is typically based on part size and complexity and the need for particular models/versions of primary and secondary processing equipment.

**Manufacturing Overhead Rate Contributors and Calculations**

In this analysis burden is defined in terms of an "inclusion/exclusion" list as follows:

Burden costs **do not** include:

- manufacturing material costs
- manufacturing labor costs
  - direct labor
  - indirect labor
  - maintenance repair and other (MRO) labor
- mark-up
  - end-item scrap
  - corporate SG&A expenses
  - profit
  - ED&T/R&D costs expenses
- tooling (e.g., mold, dies, gauges, fixtures, dedicated pallets )
- packaging costs
- external shipping and handling costs

Burden costs **do** include:

- rented and leased equipment
- primary and secondary process support manufacturing equipment depreciation
- plant office equipment depreciation
- utilities expense
- insurance costs (fire and general)
- municipal taxes
- plant floor space (equipment and plant offices)
- maintenance of manufacturing equipment (non-labor)
- maintenance of manufacturing building (general, internal and external, parts, and labor)
- operating supplies (consumables)
- perishable and supplier-owned tooling
- all other plant wages (excluding direct, indirect and MRO labor)
- returnable dunnage maintenance (includes allowance for cleaning and repair)
- intra-company shipping costs

As shown, burden includes both fixed and variable costs. Generally, the largest contribution to the fixed burden costs are the investments associated with primary and secondary process support equipment. The single largest contributor to the variable burden rate is typically utility usage.

**Acquiring Manufacturing Overhead Data**

Because there is very limited publicly available data on manufacturing overhead rates for the industry sectors included in this analysis, overhead rates have been developed from a combination of internal knowledge and experience at FEV and Munro, supplier networks, miscellaneous publications, reverse costing exercises, and "ground-up" manufacturing overhead calculations.

For ground-up calculations, a generic "Manufacturing Overhead Calculator Template" was created. The template consists of eight sections:

- General Manufacturing Overhead Information
- Primary Process Equipment
- Process Support Equipment
- General Plant & Office Hardware/Equipment
- Facilities Cost
- Utilities
- Plant Salaries
- Calculated Hourly Burden Rate

The hourly burden rate calculation for a 500 ton (T) injection mold machine is used as an example in the following paragraphs. The General Manufacturing Overhead Information section, in addition to defining the burden title (Injection Molding, Medium Size and/or Moderate Complexity) and description (Injection Molding Station, 500T Press), also defines the equipment life expectancy (12 years), yearly operating capacity (4,700 hours), operation efficiency (85%), equipment utilization (81.99%), and borrowing cost of money (8%). These input variables support many of the calculations made throughout the costing template.

The Primary Process Equipment section (500T Horizontal Injection Molding Machine) calculates the annual expense ($53,139) associated with equipment depreciation over the defined life expectancy. A straight-line-depreciation method, with zero end of life value, is assumed for all equipment. Included in the cost of the base equipment are several factors such as sales tax, freight, installation, and insurance. In addition, a maintenance, repair and other (MRO) expense (other than MRO labor, which is covered as part of the overall labor cost), calculated as a percentage of the primary process equipment cost, is included in the development of the manufacturing overhead.

The Process Support Equipment section (e.g., Chiller, Dryer, Thermal Control Unit-Mold), similar to the Primary Process Equipment section, calculates the annual expense ($6,121) associated with process support equipment depreciation.

The General Plant and Office Hardware/Equipment section assigns an annual contribution directed toward covering a portion of the miscellaneous plant and office hardware/equipment costs (e.g., millwright, electrician, and plumbing tool crib, production/quality communication, data tracking and storage, general material handling equipment, storage, shipping and receiving equipment, general quality lab equipment, office equipment). The contribution expense ($2,607) is calculated as a percent of the annual primary and process support equipment depreciation costs.

The Facilities Cost section assigns a cost based on square footage utilization for the primary equipment ($4,807), process support equipment ($3,692), and general plant and office hardware/equipment ($6,374). The general plant and office hardware/equipment floor space allocation is a calculated percentage (default 75%) of the derived primary and process support equipment floor space. The expense per square foot is $11.50 and covers several cost categories such as facility depreciation costs, property taxes, property insurance, general facility maintenance, and general utilities.

The Utilities section calculates a per-hour utility expense for both primary equipment ($9.29/hour) and process support equipment ($3.51/hour) based on equipment utility usage specifications. Some of the utility categories covered in this section include: electricity at $0.10/kW-hr, natural gas at $0.00664/cubic foot, and water at $0.001/gallon. General plant and office hardware/equipment utility expenses are covered as part of the facility cost addressed in the previous paragraph (i.e., $11.50/square foot).

The Plant Salary section estimates the contribution of manufacturing salaries (e.g., plant manager, production manager, quality assurance manager) assigned to the indirect participation of primary and process support equipment. An estimate is made on the average size of the manufacturing facility for this type of primary process equipment. There are six established manufacturing facility sizes and corresponding salary payrolls. Each has a calculated salary cost/square foot. Based on the combined square footage utilization of the primary, process support, and general plant and office equipment, an annual salary contribution cost is calculated ($6,625).

The final section, Calculated Hourly Burden Rate, takes the calculated values from the previous sections and calculates the hourly burden rate in three steps: (1) 100% efficiency and utilization ($30.54/hour); (2) user-defined efficiency with 100% utilization ($35.12/hour); and (3) both user-defined efficiency and utilization ($38.79/hour).

The majority of primary process equipment groups (e.g., injection molding, aluminum die casting, forging, stamping and forming) in the manufacturing overhead database are broken into five to ten burden rate subcategories based on processing complexity and/or size, as discussed in the manufacturing overhead review. For any given category, there will often be a range of equipment sizes and associated burden rates which are averaged into a final burden rate. The goal of this averaging method is to keep the database compact while maintaining high costing resolution.

In the example of the 500T injection molding press burden rate, the calculated rate ($38.79) was averaged with three other calculated rates (for 390T, 610T and 720T injection mold presses) into a final burden rate called “Injection Molding, Medium Size and/or Moderate Complexity.” The final calculated burden rate of $50.58/hour is used in applications requiring injection molding presses in the range of 400-800 tons.

The sample calculation of the manufacturing overhead rate for an injection molding machine above is a simple example highlighting the steps and parameters involved in calculating overhead rates. Regardless of the complexity of the operation or process, the same methodology is employed when developing overhead rates.

As discussed, multiple methods of arriving at burden rates are used within the cost analysis. Every attempt is made to acquire multiple data points for a given burden rate as a means of validating the rate. In some cases, the validation is accomplished at the final rate level and in other cases multiple pieces of input data, used in the calculation of a rate, are acquired as a means of validation.

#### 2.4.1.2.4 Mark-up (Scrap, SG&A, Profit, ED&T) Database

All mark-up rates for Tier 1 and Tier 2/3 automotive suppliers referenced throughout the cost analysis can be found in the Mark-up Database, except in those cases where unique component tolerances, performance requirements, or some other unique feature dictates a special rate. In cases where a mark-up rate is “flagged” within the costing worksheet, a note is included which describes the assumption differences justifying the modified rate.

For this cost analysis study, four mark-up sub-categories were used in determining an overall mark-up rate: (1) end-item scrap allowance, (2) SG&A expenses, (3) profit, and (4) ED&T/R&D expenses. Additional details for each subcategory are discussed following.

The layout of the Mark-up Database is similar to the Manufacturing Overhead Database in that the first tier of the Mark-up Database is arranged by the primary manufacturing process groups (e.g., thermoplastic processing, thermoset processing, and casting). The second tier subdivides the primary manufacturing process groups into primary processing equipment groups (e.g., thermoplastic processing is subdivided into injection molding, blow or rotational molding, and pressure or vacuum form molding). The third and final tier of the database increases the resolution of the primary processing equipment groups and defines the applicable mark-up rates. Similar to the overhead manufacturing rates, size and complexity of the parts being manufactured will direct the process and equipment requirements, as well as investments. This, in turn, will have a direct correlation to mark-up rates.

**Mark-up Rate Contributors and Calculations**

Mark-up, in general, is an added allowance to the Total Manufacturing Cost to cover end-item scrap, SG&A, profit and ED&T expenses. The following are additional details on what is included in each mark-up category:

<u>End-Item Scrap Mark-up</u> is an added allowance to cover the projected manufacturing fall-out and/or rework costs associated with producing a particular component or assembly. In addition, any costs associated with in-process destructive testing of a component or assembly are covered by this allowance. As a starting point, scrap allowances were estimated to be between 0.3% and 0.7% of the TMC within each primary manufacturing processing group. The actual assigned value for each category is an estimate based on size and complexity of the primary processing equipment as shown in **Table 2.4-2**.

When published industry data or consultation with an industry expert improves estimate accuracy for scrap allowance associated with a generic manufacturing process (e.g., 5% for sand casting, investment casting), the Mark-up Database is updated accordingly. In cases where the manufacturing process is considered generic, but the component performance requirements drive a higher fall-out rate (e.g., 25% combined process fallout on turbocharger turbine wheels), then the scrap mark-up rate would only be adjusted in the Manufacturing Assumption Quote Summary (MAQS) worksheet.

<u>Selling, General, and Administrative (SG&A) Mark-up</u> is also referred to as corporate overhead or non-manufacturing overhead costs. Some of the more common cost elements of SG&A are:

- Non-manufacturing, corporate facilities (building, office equipment, utilities, maintenance expenses, etc.)
- Corporate salaries (President, Chief Executive Officers, Chief Financial Officers, Vice Presidents, Directors, Corporate Manufacturing, Logistics, Purchasing, Accounting, Quality, Sales, etc.)
- Insurance on non-manufacturing buildings and equipment
- Legal and public relation expenses
- Recall insurance and warranty expenses
- Patent fees
- Marketing and advertising expenses
- Corporate travel expenses

SG&A, like all mark-up rates, is an applied percentage to the Total Manufacturing Cost. The default rates for this cost analysis range from 6% to 7% within each of the primary processing groups. The actual values, as with the end-item scrap allowances, vary within these ranges based on the size and complexity of the part, which in turn is reflected in the size and complexity of the processing equipment as shown in **Table 2.4-2**. To support the estimated SG&A rates (which are based on generalized OEM data), SG&A values are extracted from publicly traded automotive supplier 10-K reports.

Profit Mark-up is the supplier's or OEM's reward for the investment risk associated with taking on a project. On average, the higher the investment risk, the larger the profit mark-up that is sought by a manufacturer.

As part of the assumptions list made for this cost analysis, it is assumed that the technology being studied is mature from the development and competition standpoint. These assumptions are reflected in the conservative profit mark-up rates which range from 4% to 8% of the Total Manufacturing Cost. The profit mark-up ranges selected from this cost analysis are based on generalized historical data from OEMs and suppliers.

As detailed with the preceding mark-up rates, the actual assigned percentage is based on the supplier processing equipment size and complexity capabilities (**Table 2.4-2**).

ED&T Mark-up: the ED&T used for this cost analysis is a combination of "Traditional ED&T" plus R&D mark-up.

Traditional ED&T may be defined as the engineering, design and testing activities required to take an "implementation ready" technology and integrate it into a specific vehicle application. The ED&T calculation is typically more straight-forward because the tasks are predefined. R&D, defined as the cost of the research and development activities required to create a new (or enhance an existing) component/system technology, is often independent of a specific vehicle application. In contrast to ED&T, pure R&D costs are very difficult to predict and are very risky from OEM and supplier perspectives in that these costs may or may not result in a profitable outcome.

For many automotive suppliers and OEMs, traditional ED&T and R&D are combined into one cost center. For this cost analysis, the same methodology has been adopted, creating a combined traditional ED&T and R&D mark-up rate simply referred to as ED&T.

Royalty fees, as the result of employing intellectual property, are also captured in the ED&T mark-up section. When such cases exist, separate lines in the Manufacturing Assumption & Quote Summary (MAQS) worksheet are used to capture these costs. These costs are in addition to the standard ED&T rates. The calculation of the royalty fees are on a case by case basis and information regarding the calculation of each fee can be found in the individual MAQS worksheets where applicable.

**Table 2.4-2: Standard Mark-up Rates Applied to Tier 1 and Tier 2/3 Suppliers Based on Size and Complexity Ratings**

| Primary Manufacturing Equipment Group | End Item Scrap Mark-up | SG&A Mark-up | Profit Mark-up | ED&T Mark-up | Total Mark-up |
|---|---|---|---|---|---|
| Tier 2 /3 – Large Size, High Complexity, | 0.7% | 7.0% | 8.0% | 2.0% | 17.7% |
| Tier 2 /3 – Medium Size, Moderate Complexity, | 0.5% | 6.5% | 6.0% | 1.0% | 14.0% |
| Tier 2 /3 – Small Size, Low Complexity | 0.3% | 6.0% | 4.0% | 0.0% | 10.3% |
| | | | | | |
| Tier 1 Complete System/Subsystem Supplier (System/Subsystem Integrator) | 0.7% | 7.0% | 8.0% | 6.0% | 21.7% |
| T1 High Complexity Component Supplier | 0.7% | 7.0% | 8.0% | 4.0% | 19.7% |
| T1 Moderate Complexity Component Supplier | 0.5% | 6.5% | 6.0% | 2.5% | 15.5% |
| T1 Low Complexity Component Supplier | 0.3% | 6.0% | 4.0% | 1.0% | 11.3% |

### Assigning Mark-up Rates

The three primary steps to matching mark-up rates to a given component are:

**Step 1:** Primary manufacturing process and equipment groupings are pre-selected as part of the process to identify the manufacturing overhead rate.

**Step 2:** Manufacturing facilities are identified as OEM, T1 or T2/T3 (this identification process is discussed in more detail in the Manufacturing Assumption & Quote Summary worksheet section).

**Step 3:** The best-fit mark-up rate is selected based on the size and complexity of the part, which in turn is reflected in the size and complexity of the processing equipment. Note that size and complexity are considered as independent parameters when reviewing a component and the equipment capabilities (with priority typically given to "complexity").

#### 2.4.1.2.5 Packaging Database

The Packaging Database contains standardized packaging options available for developing packaging costs for components and assemblies. In general only packaging costs required to transport a component/assembly from a Tier 1 to an OEM facility (or one facility to another at the same OEM) are calculated in detail. For Tier 2/3 suppliers of high- and low-impact components, as well as purchased parts, the Tier 1 mark-up is estimated to cover the packaging as well as shipping expenses.

All core packaging items (e.g., containers, pallets, totes) referenced in the database are considered returnable dunnage. Internal packaging (e.g., tier pads, dividers, formed trays) are also considered returnable with the exception of a few items that are expendable. The cost to clean and maintain returnable dunnage is assumed to be covered by the manufacturing overhead rate.

As stated earlier it was assumed packaging changes, and associates costs, were cost neutral in the Silverado mass reduction analysis. This is based on the consideration that packaging costs are generally a function of part volume versus part mass. In the analysis, some components increased in volume, some decreased, and others remained constant. Because of the overall small changes in packaging volume, to an already minor cost driver, packing cost differentials were assumed negligible.

#### 2.4.1.2.6 Shipping Costs

In the cost analysis, shipping costs are accounted for by one of three factors: (1) Indirect Cost Multiplier (ICM), (2) total mark-up allowance, or (3) manufacturing overhead. Further, shipping costs are always considered freight on board (FOB) the shipper's dock, with the exception of intra-company transportation. Following are the four shipping scenarios encountered in the cost analysis and how each case is handled.

In the first two cases, OEM and supplier intra-company transportation, shipping costs are accounted for as part of the manufacturing overhead rate. It is assumed that the OEM or supplier would either have their own transportation equipment and/or subcontract for this service. In either case the expense is binned to manufacturing overhead.

The third case is Tier 1 shipments to an OEM facility. As stated previously the shipments are FOB the shipper's dock and thus the OEM is responsible for the shipping expense. The ICM is assumed to cover the OEM's expense to have all parts delivered to the applicable OEM manufacturing facilities.

The final case is Tier 2/3 shipments to the Tier 1 facility. Generally, the Tier 1 supplier is allowed a mark-up on incoming purchased parts from Tier 2/3 suppliers. The mark-up covers many costs including the shipping expenses to have the part delivered onto the Tier 1 supplier's dock. Further, the mark-up can either be a separate mark-up only applied to incoming purchased parts, or accounted for by the mark-up applied to the

TMCs. In the former, the purchase part content would not be included in the final mark-up calculation (i.e., Mark-up = (TMC - Purchase Parts cost) x Applicable Mark-up Rate).

For this cost analysis, the latter case is chosen using the same mark-up rate for all Tier 1 value-added manufacturing as well as all incoming purchase parts.

#### 2.4.1.2.7 Process Parameter Models

**Process Parameter Models (PPM)** are custom models used to calculate key processing factors such as material usage, equipment selection, tool size and complexity, order of operations, and cycle times.

Two types of basic PPM exist: (1) Generic PPM, and (2) Custom PPMs. Generic PPM have been developed for generic operations (i.e., injection molding, stamping, forging die casting, gear cutting, CNC machining, CNC turning, etc.). Custom PPM are developed for unique operations or a series of unique operations such as assembling a battery pack. Smaller sub-models are pulled together to create a custom PPM. Because the models are developed for a custom assembly they need to be updated/modified for alternative analyses. Custom models which are repeatedly used are eventually converted into generic models minimizing repetitive re-construction.

Process Parameter Model inputs and outputs are based on the primary process type (e.g., stamping, injection molding, turning, milling, die casting, assembly). Examples of model inputs include:

- Material specification
- Finish specification
- Finished mass
- Wall thickness
- Part package envelop
- Part projected area
- Feature type
- Feature count
- Feature location
- Number of cores
- Parting line locations
- Part cleanliness criteria
- Serial, parallel, batch processing

Examples of model outputs include the following:

- Primary equipment selection (i.e., type and size)

- Secondary equipment selection , if applicable
- Total material usage (i.e., post process mass and in process material usage)
- Perishable materials usage (e.g., sand, solvent, binder, tools, etc.)
- Takt time build-up
- Tooling requirements
- Tooling cost build-up
- Tooling life projections
- Energy consumption

Output data from the PPM is used to support the selection of the appropriate manufacturing overhead rates. For example in injection molding, the PPM would calculate the estimate machine size (i.e., 200T, 600T, 800T, etc.). The cost engineer would then select the matching machine size in the manufacturing overhead database and enter the corresponding rate in the Manufacturing Assumption and Quote Summary (MAQS) worksheet. Other output parameters such as "Total Material Usage" and "Takt Time" are manually imported into the MAQS worksheets along with other supporting cost parameters from the databases. Additional details on how database and process parameter model information is used to calculate final costs in the MAQS worksheet is provided in the section that follows.

All process parameter cost models are developed using a combination of published equipment data, published processing data, actual supplier production data, and/or subject matter expert consultation.

#### 2.4.1.3 Step 3: Cost Model Development

Once all components/assemblies requiring cost analysis are identified, the vehicle level Comparison Bill of Materials (CBOMs) are updated to reflect the type of costing that will be employed (i.e., commodity/benchmark or detailed/calculated). The objective is to minimize costing of mass-produced commodity type components allowing for more detailed costing on key high impact components and processes which may not be considered mainstream in-terms of production volumes and market maturity. In addition to volume and maturity considerations, the value of the components also played into the decision of selecting either commodity or detailed costing.

##### 2.4.1.3.1 <u>Commodity and Benchmark Costing</u>

The Commodity and Benchmark Costing methodology analysis is generally divided into three levels of costing. The first level of costing is for low-value/low-impact commodity-type components. Costs for these types of components (e.g., bolts, nuts, washers, seals, retainers, etc.) are taken from exiting FEV and Munro commodity databases.

The second level of costing is for moderate- to high-impact commodity-type components (e.g., solenoids, sensors, wire harnesses, etc.). Based on high mass-production volumes, product maturity, and market place competition, acquiring reliable component/assembly costs is possible. If a direct component match is not possible, the team will conduct a teardown on the commodity component to assess differences to a like component in the costing databases. Adjustment/scaling factors are then developed to account for any manufacturing/commercial differences. If the component does not exist in the manufacturing costing databases, the team consults with industry subject matter experts to acquire pricing.

The third level of costing involves scaling benchmark data for high-impact custom-fabricated and assembled components. From existing component cost data, from previous cost and benchmark studies (w/ similar boundary conditions), scaling factors are developed based on attribute differences between the parts under evaluation and parts in the database. The scaling factors are applied to the benchmark costs to arrive at component costs applicable to the analysis.

For the Silverado mass reduction and cost analysis, the use of commodity pricing was generally limited to levels one and two.

#### 2.4.1.3.2 Detailed Cost Modeling

The detail cost modeling methodology employed in Step 3 (overall costing process) is further broken down into three primary processes sub-steps (**Figure 2.4-4**): (3A) the development of detailed production process maps/flow charts (P-flows), (3B) the transfer and processing of key information from the P-flows into standardize Manufacturing Assumption and Quote Summary (MAQS) worksheets, and (3C) the summation of costs, at each level of the product structure (i.e., assembly, sub-subsystem, subsystem, system, vehicle) in Cost Model Analysis Templates (CMATs). Supporting these two primary processes with key input data are the process parameter models and the costing databases (e.g., material [price/kg], labor [$/hour], manufacturing overhead [$/hour], mark-up [% of manufacturing cost], and packaging [$/packaging type]). **Figure 2.4-4** highlights the primary detailed costing steps shown in **Figure 2.4-3** (Cost Methodology Steps for Powertrain, Chassis and Trim Evaluation Group).

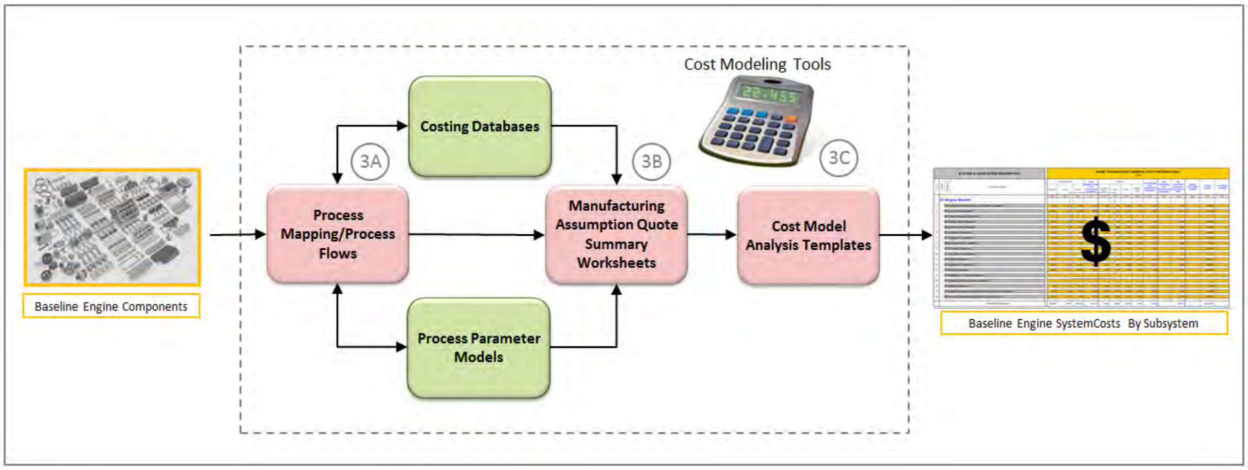



**Figure 2.4-4: Primary Process Steps in Detailed Cost Modeling**

### *2.4.1.3.2.1 Step 3A: Process Mapping/Process Flow Charts*

Process flow charts, depending on their defined function and the end user, can vary widely in the level of detail contained. They can range from simple block diagrams showing the general steps involved in the manufacturing or assembly of an item, to very detailed process flow charts breaking out each process step in fine detail capturing key manufacturing variables. For this cost analysis, detailed P-flows (which will also be referred to as process maps) are used to identify all the steps involved in manufacturing a product (e.g., assembly, machining, welding, forming), at all levels (e.g., system, subsystem, assembly and component).

For example, in a front brake system scenario, process flows would exist for the following: (1) at the ***component level***, the manufacturing of every component within the front brake caliper sub-assembly. This would include such components as the caliper housing, caliper mounting bracket, caliper piston, etc. (unless considered a purchase part – i.e., bleeder fitting, brake pads, piston seal, fastening bolts, etc.); (2) at the ***assembly level***, the assembly of all the individual components to produce the caliper assembly module; and (3) at the ***subsystem level,*** the assembly of the caliper module onto the front knuckle module (including the splash shield, bearing hub, rotor, etc.). In this example, the front rotor/drum and shield subsystem is one of several subsystems (e.g., rear rotor/drum and shield subsystem, parking brake and actuation subsystem, brake actuation subsystem, and power brake subsystem) making up the overall vehicle braking system. Each subsystem, if it is costed in the analysis, would have its own process map broken out using this same process methodology.

In addition to detailing pictorially the process steps involved for a given manufacturing process, having key information (e.g., equipment type, tooling configuration, material type and usage, cycle times, handling requirements, number of operators) associated with each step is imperative. Understanding the steps and the key process parameters together creates the costing roadmap for any particular manufacturing process.

Due to the vast and complex nature of P-flows associated with some of the larger systems and subsystems under analysis, having specialized software which can accurately and consistently create and organize the abundant number of detailed P-flows becomes a considerable advantage. For this cost analysis Design Profit® software is utilized for producing and managing the process flows and integrating key costing information.

The Design Profit methodology is a quantitative, analytical tool used to symbolically map a single component or product assembly, providing a consistent means of capturing every step of the process while consistently capturing various metrics associated with the total cost of manufacturing. **Figure 2.4-5** shows an example of a process map created by the Design Profit software. Simply explained, the symbols which make up the process map each contain essential pieces of information required to develop a cost for a particular operation or process.

For example, in a metal stamping process, the basic geometry of the part, quantity and complexity of part features, material gauge thickness, and material selection are examples of the input parameters used in the calculation of the output process parameters (e.g., press size, press cycle time, stamping blank size). As discussed in Section 2.4.1.2.7 (Process Parameter Models), input data captured in the process symbols is entered into Process Parameter Models (PPMs) to arrive at the output costing parameters.

For simpler serial processes, and multiple-step, serial-type processes (e.g., assembly process, metal removal process) process parameter models are created directly in Design Profit®. Generally, these type process parameter models are single input type models; e.g., weld time/linear millimeter of weld, cutting time/square millimeter of cross-sectional area, and drill time/millimeter of hole depth. The output parameters, such as process takt time, is captured within the process map symbol; imported into a MAQS worksheet in the Step 3B of the process.

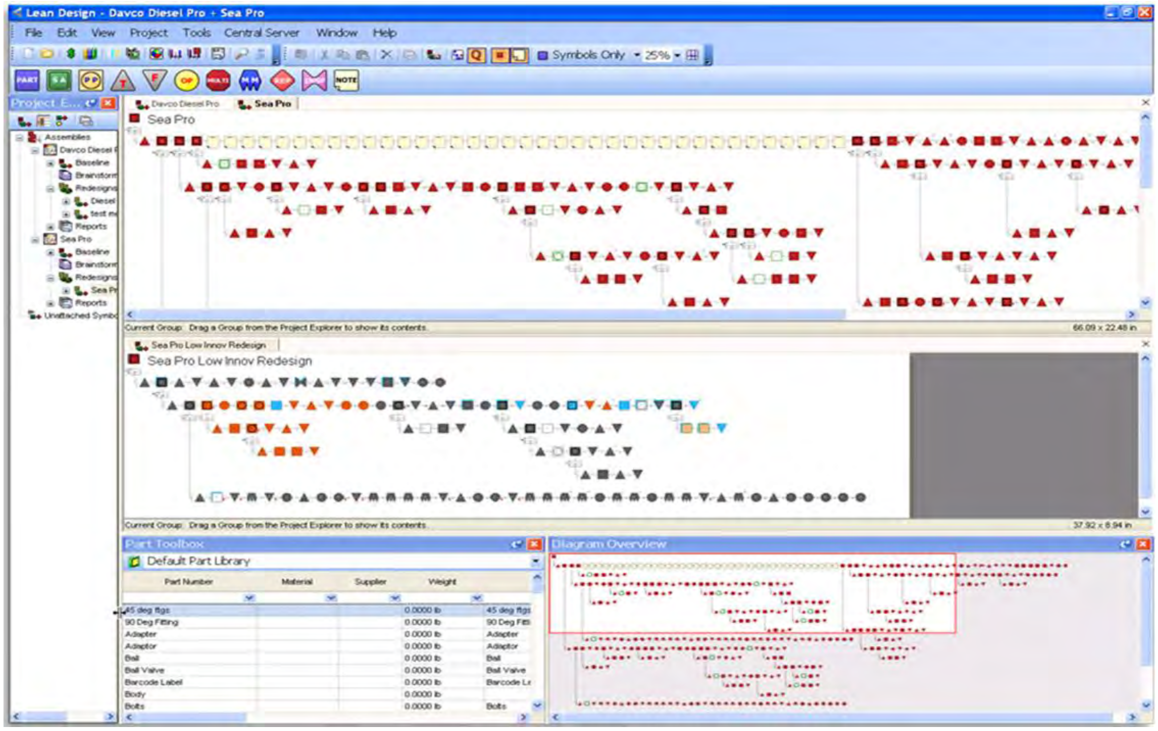


**Figure 2.4-5: Example of Design Profit® Mapping/Costing Software**

### *2.4.1.3.2.2 Step 3B: Manufacturing Assumption – Quote Summary (MAQS) Worksheet*

The second major step in the cost analysis process involves taking the key information from the Process Flows, Process Parameter Models and Databases, and uploading it into a standardized quote worksheet. The quote worksheet, referred to as the Manufacturing Assumption and Quote Summary (MAQS) worksheet, is essentially a modified generic OEM quoting template. Every assembly included in the cost analysis (excluding commodity purchased parts) has a completed MAQS worksheet capturing all the cost details for the assembly. For example, all the components and their associated costs, required in the manufacturing of a brake caliper module assembly, will be captured in the caliper module assembly MAQS worksheet. In addition, a separate MAQS worksheet detailing the cost associated with assembling the caliper assembly to the vehicle front suspension knuckle, along with any other identified front corner brake sub-subsystem components, would be created.

**Main Sections of Manufacturing Assumption and Quote Summary Worksheet**

The MAQS worksheet, as shown in **Figure 2.4-6** and **Figure 2.4-7**, contains seven major sections. At the top of every MAQS worksheet is an information header ***(Section A)***, which captures the basic project details along with the primary quote assumptions. The project detail section references the MAQS worksheet back to the applicable CBOM. The primary quote assumption section provides the basic information needed to put together a quote for a component/assembly. Some of the parameters in the quote assumption section are automatically referenced/linked throughout the MAQS worksheet, such as capacity planning volumes, product life span, and OEM/T1 classification. The remaining parameters in this section including facility locations, shipping methods, packing specifications, and component quote level are manually considered for certain calculations.

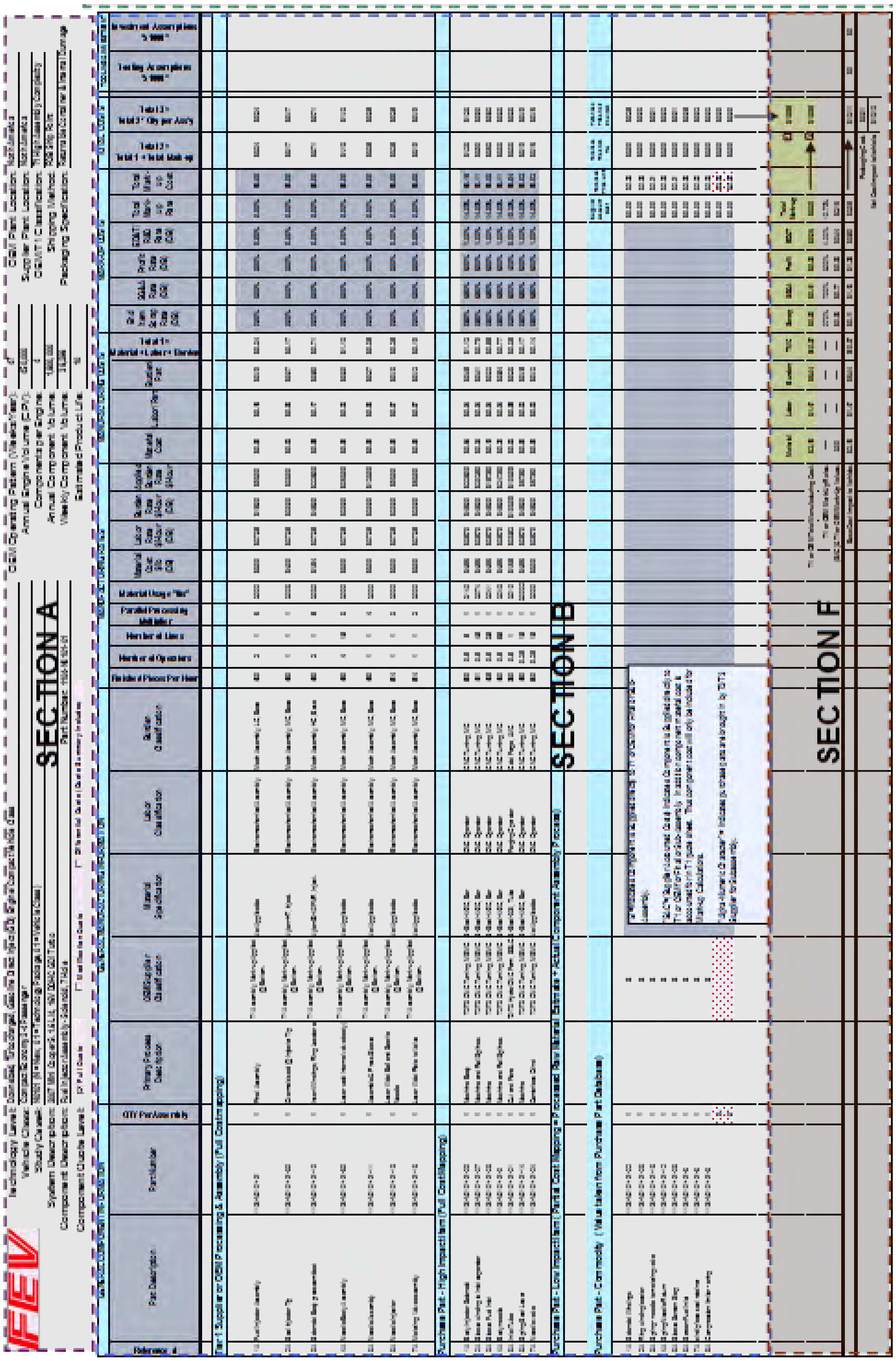



**Figure 2.4-6: Sample MAQS Costing Worksheet (Part 1 of 2)**

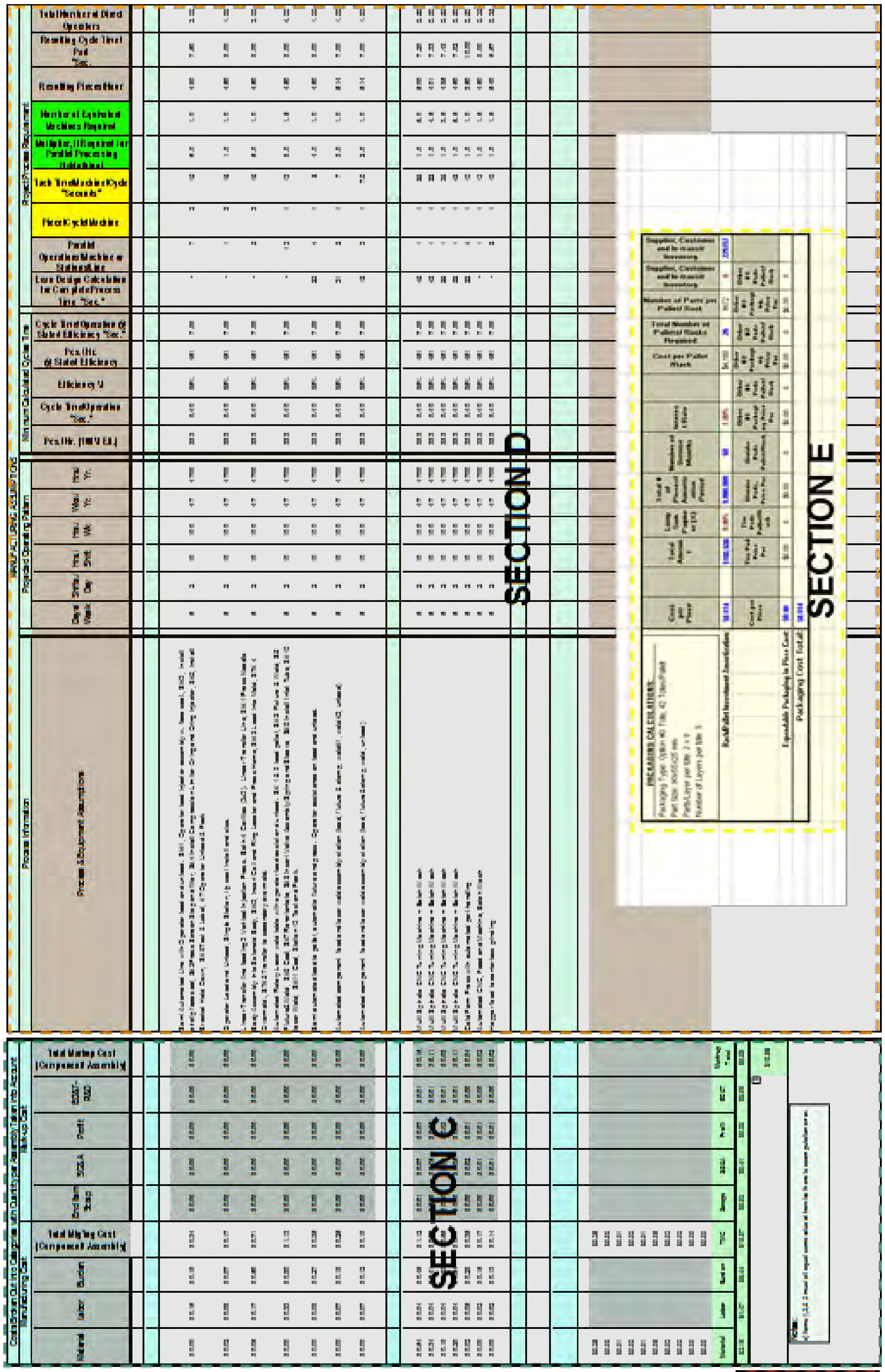



**Figure 2.4-7: Sample MAQS Costing Worksheet (Part 2 of 2)**

Two parameters mentioned above whose functions perhaps are not so evident from their names are the "OEM/T1 classification" and "component quote level."

The "OEM/T1 classification" parameter addresses who is taking the lead on manufacturing the end-item component, the OEM or Tier 1 supplier. Also captured is the OEM or Tier 1 level, as defined by size, complexity, and expertise level. The value entered into the cell is linked to the Mark-up Database, which will up-load the corresponding mark-up values from the database into the MAQS worksheet. For example, if "T1 High Assembly Complexity" is entered in the input cell, the following values for mark-up are pulled into the worksheet: Scrap = 0.70%, SG&A = 7%, Profit = 8.0% and ED&T = 4%. These rates are then multiplied by the TMC at the bottom of the MAQS worksheet to calculate the applied mark-up as shown in **Figure 2.4-8**.

The process for selecting the classification of the lead manufacturing site (OEM or T1) and corresponding complexity (e.g., High Assembly Complexity, Moderate Assembly Complexity, Low Assembly Complexity) is based on the team's knowledge of existing value chains for same or similar type components.

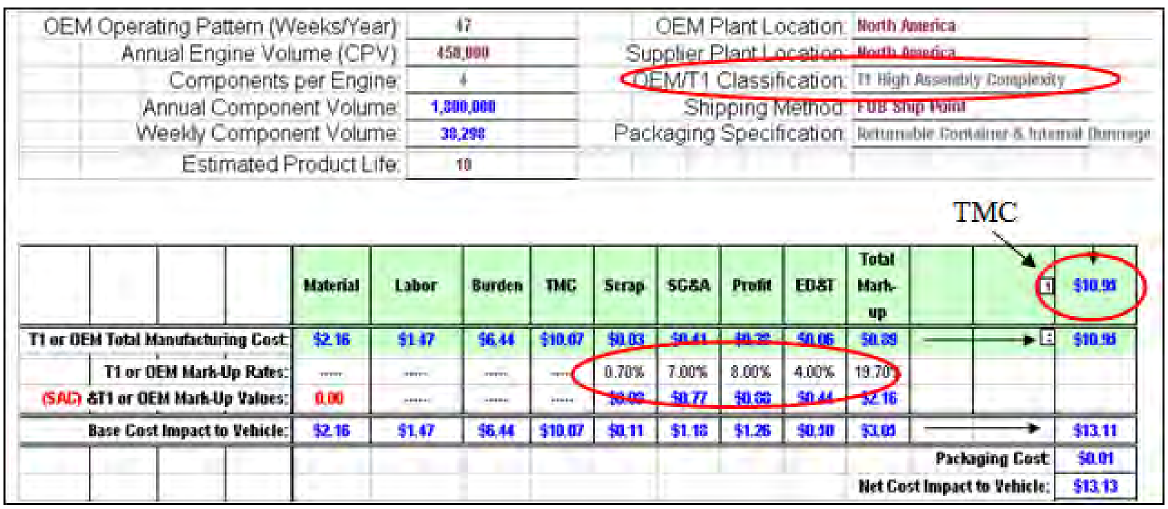



**Figure 2.4-8: Excerpt Illustrating Automated Link between OEM/T1 Classification Input in MAQS Worksheet and the Corresponding Mark-up Percentages Uploaded from the Mark-up Database**

The "component quote level" identifies what level of detail is captured in the MAQS worksheet for a particular component/assembly, full quote, modification quote, or differential quote. When the "full quote" box is checked, it indicates all manufacturing costs are captured for the component/assembly. When the "modification quote" box is checked, it indicates only the changed portion of the component/assembly has been quoted. A differential quote is similar to a modification quote with the exception that information from both technology configurations, is brought into the same MAQS worksheet, and a differential analysis is conducted on the input cost attributes versus the output cost attributes. For example, if two brake boosters (e.g., the production stock booster and the mass-reduced booster) are being compared for cost, each brake booster can have its differences quoted in a separate MAQS worksheet (modification quote) and the total cost outputs for each can be subtracted to acquire the differential cost. Alternatively in a single MAQS worksheet the cost driving attributes for the differences between the booster's (e.g., mass difference on common components, purchase component differences, etc.) can be offset, and the differential cost calculated in a single worksheet. The differential quote method is typically employed on those components with low differential cost impact to help minimize the number of MAQS worksheets generated.

From left to right, the MAQS worksheet is broken into two main sections as the name suggests a quote summary section ***(Section B),*** and manufacturing assumption section ***(Section D).*** The manufacturing assumption section, positioned to the right of the quote summary section, is where the additional assumptions and calculations are made to convert the serial processing operations from Lean Design into mass production operations. Calculations made in this section are automatically loaded into the quote summary section. The quote summary section utilizes this data along with other costing database data to calculate the total cost for each defined operation in the MAQS worksheet.

Note that "defined operations" are all the value-added operations required to make a component or assembly. For example, a high-pressure fuel injector may have 20 base-level components which all need to be assembled together. To manufacture one of the base level components there may be as many as two or three value-added process operations (e.g., cast, heat treat, and machine). In the MAQS worksheet each of these process operations has an individual line summarizing the manufacturing assumptions and costs for the defined operation. For a case with two defined operations per base level component, plus two subassembly and final assembly operations, there could be as many as 40 defined operations detailed in the MAQS worksheet. For ease of viewing all the costs associated with a part, with multiple value-added operations, the operations are grouped together in the MAQS worksheet.

Commodity based purchased parts are also included as a separate line in the MAQS worksheet. Although there are no supporting manufacturing assumptions and/or calculations required since the costs are provided as total costs.

From top to bottom, the MAQS worksheet is divided into four quoting levels in which both the value-added operations and commodity-based purchase parts are grouped: (1) Tier 1 Supplier or OEM Processing and Assembly, (2) Purchase Part – High Impact Items, (3) Purchase Part – Low Impact Items, and (4) Purchase Part – Commodity. Each quoting level has different rules relative to what cost elements are applicable, how cost elements are binned, and how they are calculated.

Items listed in the ***Tier 1 Supplier or OEM Processing and Assembly*** section are all the assembly and subassembly manufacturing operations assumed to be performed at the main OEM or T1 manufacturing facility. Included in manufacturing operations would be any in process attribute and/or variable product engineering characteristic checks. For this quote level, full and detailed cost analysis is performed (with the exception of mark-up which is applied to the TMC at the bottom of the worksheet).

***Purchase Part – High Impact Items*** include all the operations assumed to be performed at Tier 2/3 (T2/3) supplier facilities and/or T1 internal supporting facilities. For this quote level detailed cost analysis is performed, including mark-up calculations for those components/operations considered to be supplied by T2/3 facilities. T1 internal supporting facilities included in this category do not include mark-up calculations. As mentioned above, the T1 mark-up (for main and supporting facilities) is applied to the TMC at the bottom of the worksheet.

***Purchase Part – Low Impact Items*** are for *higher priced* commodity based items which need to have their manufacturing cost elements broken out and presented in the MAQS sheet similar to high impact purchase parts. If not, the material cost group in the MAQS worksheet may become distorted since commodity based purchase part costs are binned to material costs.

At the bottom of the MAQS worksheet ***(Section F)***, all the value-added operations and commodity-based purchase part costs, recorded in the four quote levels, are automatically added together to obtain the TMC. The applicable mark-up rates based on the T1 or OEM classification recorded in the MAQS header are then multiplied by the TMC to obtain the mark-up contribution. Adding the TMC and mark-up contribution together, a subtotal unit cost is calculated.

Important to note is that throughout the MAQS worksheet, all seven cost element categories (material, labor, burden, scrap, SG&A, profit, and ED&T) are maintained in the analysis. ***Section C,*** MAQS breakout calculator, which resides between the quote summary and manufacturing assumption sections, exists primarily for this function.

The last major section of the MAQS worksheet is the packaging calculation, ***Section E***. In this section of the MAQS worksheet a packaging cost contribution is calculated for each part based on considerations such as packaging requirements, pack densities, volume assumptions, stock, and/or transit lead times. As previously mentioned, for the purpose of this study component/assembly packaging costs were considered to be neutral due to the relative size envelope of these parts not changing significantly between the production stock and mass-reduced parts.

### Marketplace Validation

Marketplace validation is the process by which individual parts, components, and/or assemblies are cross-checked with costing data developed by entities and processes external to the team responsible for the cost analysis. This process occurs at all stages of the cost analysis, with special emphasis is placed on cross-checking in-process costs (e.g., material costs, material selection, labor costs, manufacturing overhead costs, scrap rates, and individual component costs within an assembly).

In-process cost validation occurs when a preliminary cost has been developed for a particular part within an assembly, and the cost is significantly higher or lower than expected based on the team's technical knowledge or on pricing from similar components. In this circumstance, the cost analysis team would first revisit the costs, drawing in part/process-specific internal expertise and checking surrogate parts from previously costed bills of materials where available. If the discrepancy is still unresolved, the team would rely on automotive supplier networks, industry experts, and/or publicly available publications to validate the cost assumptions, making changes where warranted.

Cross-checking on final assembly costs also occurs within the scope of the cost analysis, mainly as a "big picture" check. Final assembly costs, in general cross-checking, are typically achieved through solicitation of industry experts. The depth of cross-checking ranges from simple comparison of cost data on surrogate assemblies to full Manufacturing Assumption and Quote Summary (MAQS) worksheet reviews.

###### *2.4.1.3.2.3 Step 3C: Cost Model Analysis Templates (CMATs)*

The Cost Model Analysis Templates (CMATs) are the documents used to display and roll-up all the costs associated with a particular subsystem, system or vehicle. At the lowest level of the hierarchy, the manufacturing assumption quote summary worksheets, associated with a particular vehicle subsystem, are directly linked to the Sub-subsystem CMAT (SSSCMAT). These Sub-subsystem cost totals are then summarized at the next level in the Subsystem CMAT (SSCMAT). All the subsystems cost breakdowns, associated with a particular system, are directly linked to the relevant System CMAT (SCMAT). Similarly, all the system cost breakdown summaries are directly linked to the Vehicle CMAT (VCMAT). The top-down layering of the incremental costs, at the various CMAT levels, paints a clear picture of the cost drivers at all levels for the adaptation of the light-weighting technology. In addition, since all of the databases, MAQS worksheets, and CMATs are linked together, the ability to understand the impact of various cost elements on the incremental cost can be readily understood. These costing variables can be easily and quickly updated within the various databases to provide a tremendous amount of flexibility in evaluating various costing scenarios and sensitivity studies.

##### 2.4.1.3.3 Incremental Tooling Calculations

As part of the mass reduction and cost analysis project, EPA requested that FEV determine the differential tooling impact for those components that were evaluated for mass reduction. Tooling Costs are defined as the dedicated tool, gauge, and fixture costs required to manufacture a part. Examples of items covered by tooling costs include injection molds, casting molds, stamping dies, weld fixtures, assembly fixtures, dedicated assembly and/or machining pallets, and dedicated gauging. For this analysis, all tooling is assumed to be owned by the OEM.

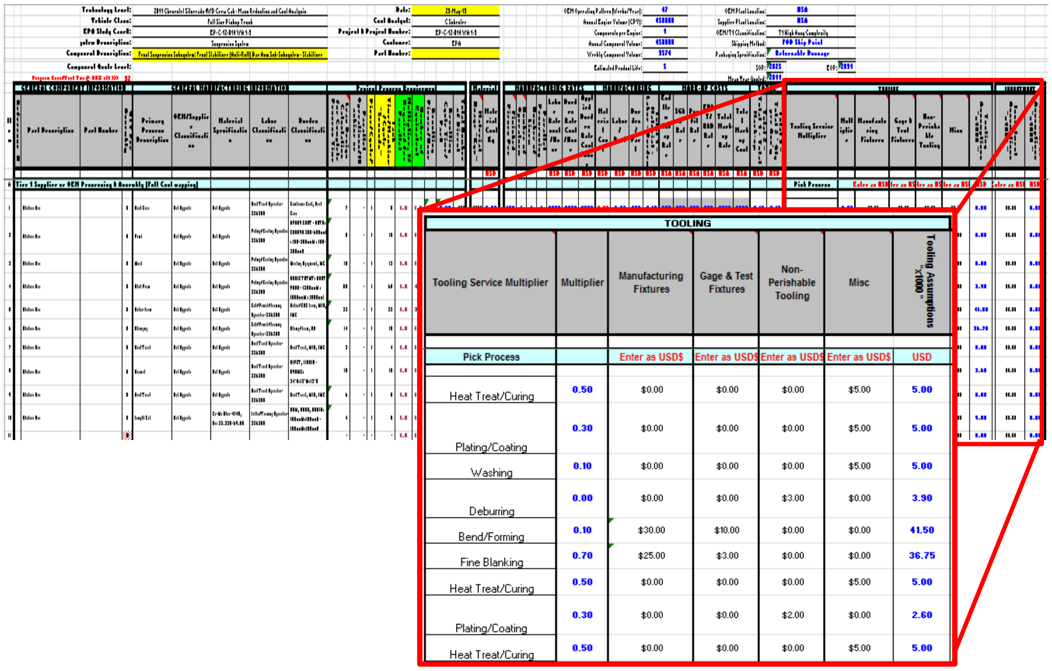
Tooling costs should not be confused with equipment and facility costs (also sometimes referred to as investment costs or capital investment costs. Investment costs include manufacturing plants, manufacturing equipment (e.g., injection mold machines, die cast machines, machining and turning machines, welding equipment, assembly lines), material handling equipment (e.g., lift forks, overhead cranes, loading dock lifts, conveyor systems), paint lines, plating lines, and heat treat equipment. Investment costs are accounted for in the manufacturing overhead rates. The tool cost analysis is an incremental analysis using a similar methodology as established for developing the incremental direct manufacturing costs. For example if a part on the production Silverado is injection-molded and the new mass reduced replacement part is injection-molded using the PolyOne injection mold process, then no further tooling analysis was conducted. The PolyOne process requires no significant tooling modifications relative to traditional injection mold tools. Conversely, if a component went from a stamped part to an injection mold part, the team would then quote the tooling needed for stamping the production stock part as well as the injection-molded mass-reduced part. The tooling cost would be the difference between these two values (+/-).

**Differential Tooling Cost Analysis Methodology**

Outlined here are the general process steps used by FEV to evaluate the differential tooling impact between the production stock Silverado components and the mass-reduced replacement components.

1) **Assemble and assign teams of manufacturing expertise**
    a) Assembled team members have expertise in several key primary and secondary manufacturing processes including stamping, casting, molding and machining.
    b) When required, outside consultation resources were also utilized.
    c) Assemble and assign teams to vehicle subsystems and systems having a majority of components with fabrication processes matching team's expertise.
2) **Establish Boundary Conditions for Tooling Analysis**
    a) High volume production: 450K units/year
    b) Assumed manufacturing life: 5 years
    c) Assumed cost of borrowing money: 8%

3) **Identify mass-reduced components in the analysis potentially having an incremental tooling impact**
   a) Evaluate component manufacturing process differences between the production stock and mass-reduced components.
   b) Based on the team's assessment, if a significant tooling value difference exists between the production stock and mass reduced components, a tooling analysis is initiated.
   c) If an insignificant incremental tooling difference is identified by the team, a zero value is placed in the Manufacturing Assumption and Quote Summary (MAQS) worksheet for both the production stock component and mass-reduced alternative.
4) **Establish tooling costs for components having a potential tooling impact (components which were not evaluated in the analysis for mass reduction were excluded from the analysis up front)**
   a) Establish tooling line-up for the production Silverado components with respect to the mass-reduced components (e.g., types of tools, number of tools).
   b) Six standard tooling categories exist to establish the potential tooling line-ups:
      i) Primary Manufacturing Tools and Fixtures (e.g., molds, dies, machining fixtures, assembly fixtures, stamping tools)
      ii) End of Line Gauges and Testing Fixtures
      iii) Non-Perishable Tooling (e.g., machining cutter bodies, pick-n-place/gantries arms, guide/bushing plates)
      iv) Custom & Dedicated Gauges
      v) Bulk Processes (e.g., baskets, hangers, custom conveyors or walking arms)
      vi) OPTIONAL (to be described w/ comment box if needed)
   c) As part of the tooling assessment, consideration is also given to the following:
      i) Number of back-up tool sets
      ii) Repair frequency, complexity, and costs
      iii) Refurbishment frequency, complexity, and costs
   d) Tooling costs for each operation included in the component analysis are summed-up and entered in the tooling column of the Manufacturing Assumption and Quote Summary (MAQS) worksheet (**Figure 2.4-9**). The tooling impact is automatically summed-up at the bottom of the MAQS worksheet similar to the direct manufacturing costs for every component evaluated; both the production stock Silverado parts (baseline) and mass-reduced Silverado parts (new technology configuration).



| TOOLING | | | | | | |
|---|---|---|---|---|---|---|
| Tooling Service Multiplier | Multiplier | Manufacturing Fixtures | Gage & Test Fixtures | Non-Perishable Tooling | Misc | Tooling Assumptions "x1000" |
| Pick Process | | Enter as USD$ | Enter as USD$ | Enter as USD$ | Enter as USD$ | USD |
| Heat Treat/Curing | 0.50 | $0.00 | $0.00 | $0.00 | $5.00 | 5.00 |
| Plating/Coating | 0.30 | $0.00 | $0.00 | $0.00 | $5.00 | 5.00 |
| Washing | 0.10 | $0.00 | $0.00 | $0.00 | $5.00 | 5.00 |
| Deburring | 0.00 | $0.00 | $0.00 | $3.00 | $0.00 | 3.90 |
| Bend/Forming | 0.10 | $30.00 | $10.00 | $0.00 | $0.00 | 41.50 |
| Fine Blanking | 0.70 | $25.00 | $3.00 | $0.00 | $0.00 | 36.75 |
| Heat Treat/Curing | 0.50 | $0.00 | $0.00 | $0.00 | $5.00 | 5.00 |
| Plating/Coating | 0.30 | $0.00 | $0.00 | $2.00 | $0.00 | 2.60 |
| Heat Treat/Curing | 0.50 | $0.00 | $0.00 | $0.00 | $5.00 | 5.00 |

**Figure 2.4-9: Sample Excerpt from Mass-Reduced Front Stabilizer Bar MAQS Worksheet Illustrating Tooling Columns and Categories**

5) **Calculation of Net Differential Tooling Impact**
   a) Similar to the direct manufacturing cost roll-ups, Cost Model Analysis Templates (CMATs) are used to roll-up the tooling costs at each level of the analysis.
   b) Tooling costs are summed-up at the sub-subsystem, subsystem, system level and vehicle level.

6) **The Final step is the calculation of "Incremental Tooling Cost per Vehicle" and "Incremental Tooling Cost per Kilogram" of mass reduction at the final assessed mass-reduced vehicle**
   a) Assumptions and calculations using the vehicle differential tooling cost and mass reduction values are shown below.
   b) Additional details on incremental tooling costs by system can be found in Section 4.

**<u>Assumptions:</u>**

- Assumed Average Component Volume: 450K units per year
- Average product/tooling life: 5 years
- Cost of money: 8%
- Calculated incremental vehicle tooling cost:  Decrease $7.3M
- Calculate mass reduction/vehicle (w/ NVH countermeasures) = 510.9 kg (20.8%)

**Calculations (for the 20.8% mass reduced vehicle):**

- Investment saving growth over 5 years = \$7.3 → \$10.3M (8% growth over 5 years)
- Incremental Tooling Cost Savings per Vehicle = \$4.57 (\$10.3M tooling/[450K units/year x 5 years])
- Incremental Tooling Cost Saving per Kilogram @ Vehicle Level = \$0.009/kilogram [(\$4.57/ Vehicle) ⁄ (510.9 kg/Vehicle)]

#### 2.4.1.4 Step 4: Cost Assessment of Varying Levels of Vehicle Mass reduction

The final cost modeling task was to develop a cost curve representing the average cost per kilogram of mass reduction in relationship to percent vehicle mass reduction. Cost curves with and without secondary mass-savings were developed. The following process steps were taken to develop the cost curves:

1) Mass-reduced components and assemblies, without secondary mass-savings, were sorted from best value (lowest cost) to least value in-terms of cost per kilogram.
2) Starting at the best-value mass-reduced components and assemblies, mass reduction and costs were cumulatively added providing a mass reduction and cost total at various increments of percent vehicle mass reduction.
3) The counter measure mass allowance (50 kg) and associated cost (\$150) were then added to the cumulative mass and costs values in step two above. This was accomplished by equally allocating the counter measure mass and costs over the total vehicle mass reduction and associated costs.
4) The cumulative cost per kilogram points (points without secondary mass-savings) were then plotted with respect to percent vehicle mass reduction (green diamonds in **Figure 2.4-10**). In addition the final vehicle solution (20.8% vehicle mass reduction), identified as "Aluminum Intensive Body and HSS Intensive Frame," as well as an HSS Intensive and Aluminum Intensive vehicle solution, were added to the plot (red and blue squares respectively in **Figure 2.4-10**).
5) To establish a similar plot inclusive of secondary mass savings, the benefit from secondary mass savings was added to the points without secondary mass savings. As shown in **Executive Table 3**, the added mass and cost benefit achieved from applicable system downsizing was 83.9 kilograms and \$68.74 respectively per vehicle. These savings were based on the overall vehicle achieveing a 20% mass reduction. The added mass and cost savings are divided by the 20% mass reduction to determinine the added mass reduction and cost benefit at a give percent vehicle mass reduction. For example at 10% vehicle mass reduction an additional 42kg (83.9 kg*(10%/20%) of mass and \$34.37 (\$68.74*(10%/20%) of cost savings are realized. By adding the ratioed mass and cost benefit to the

cumulative cost per kilogram points defined in step four above a cost/kilogram versus percent vehicle mass reduction plot, inclusive of secondary mass savings, is achieved (purple triangles ▲ in **Figure 2.4-10**).

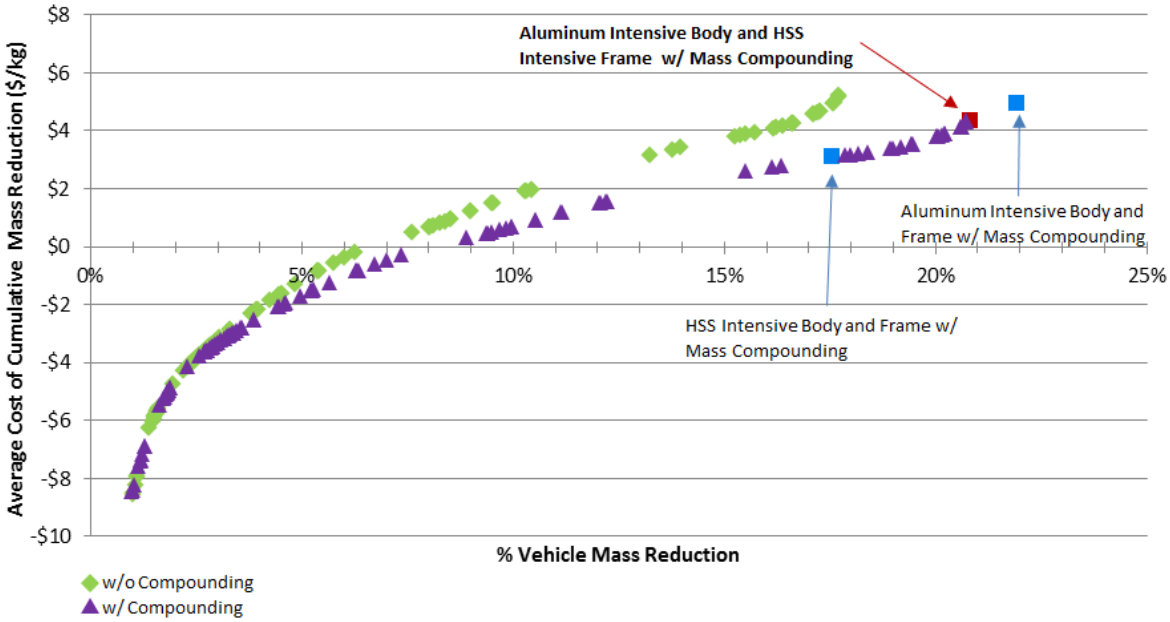



**Figure 2.4-10: Light-Duty Pickup Truck Cost Curves With and Without Mass Compounding**

## 2.4.2 Body and Frame Evaluation Group – Cost Modeling Details

### 2.4.2.1 Approach

The incremental costs for the Body and Frame components were estimated by EDAG using the Technical Cost Modeling (TCM) approach developed by the Massachusetts Institute of Technology (MIT) Materials Systems Laboratory's researchers.[19] In this method each of the elements that contribute to the total cost is individually estimated. For example, for a stamped sheet metal part, the cost model estimates the costs for each of the operations involved in the manufacturing process, starting from blanking the steel coil through the final stamping operation to fabricate the component. The final estimated total manufacturing cost and assembly cost are a sum total of all the respective cost elements including the costs for material, tooling, equipment, direct labor, energy, building and maintenance.

TCM is a comprehensive cost estimation technique accepted and utilized by multiple organizations in industry, government agencies and its national labs and academia. We attribute this acceptance to the methodology for TCM since in this model the cost of component or system is broken into costs associated to discrete manufacturing and assembly process steps and all the process assumptions are clearly defined upfront. TCM is specifically designed to assess the interaction between process input variables (e.g., equipment type and cycle time) specific to the process and the final cost. The approach is based on applying basic engineering principles and clearly defined economic and accounting principles. For these reasons, the team believes TCM is an appropriate tool for studies focused on a comparative analysis between competing designs or technologies within a company where the remaining costs are assumed to be approximately identical, as is the case with this study. The focus of this study is to compare the cost impact of certain lightweight technologies to the baseline vehicle. TCM is a suitable tool for this study providing the incremental costs of the proposed mass-reduced design along with the detailed costs elements.

### 2.4.2.2 TCM History and Usage

TCM was initially developed to support the World Auto Steel ULSAB-AVC (Advanced Vehicle Technologies), a program intended "to demonstrate and communicate steel's capability to help fulfill society's demands for safe, affordable and environmentally responsible vehicles for the 21st Century."[20] Subsequently, EDAG expanded the model

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19 Frank Field, Randolph Kirchain and Richard Roth, Process cost modeling: Strategic engineering and economic evaluation of materials technologies, JOM Journal of the Minerals, Metals and Materials Society, Volume 59, Number 10, 21-32

20 http://www.worldautosteel.org/Projects/ULSAB-AVC/Programme-Detail.aspx (last accessed February 9, 2012)

to support the Future Steel Vehicle program which assessed body structure costs while also applying future manufacturing technologies.[21] EDAG's extensive and recognized modeling work yielded a portfolio of established, consistently developed cost models available to leverage for assessing body structures, closures, and among other vehicle components or systems. For purposes of this study, the cost model was updated to align with project boundary conditions. TCM model is also employed by the Department of Energy for costing exercises for its vehicle technologies program. Other examples of TCM model application in automotive related studies include "Cost Modeling of Fuel Cell Systems for Automobiles," "Economic Assessment of Alternative Manufacturing Processes for the Camshaft[22] and Material Alternatives for the Automotive Crankshaft – A Competitive Assessment Based on Manufacturing Economics."

#### 2.4.2.3 Major Components of the Cost Model

For the Silverado mass reduction and incremental cost assessment, only the direct costs for manufacturing the parts and assembly of the parts were considered for OEM produced components and assemblies. For Tier 1-supplied components mark-up was added to the direct manufacturing costs to arrive at the Net Incremental Direct Manufacturing Cost (OEM purchase price from supplier).

The major cost elements linked to the direct manufacturing and assembly are summarized as follows:

- Fabrication costs of all the parts including tooling costs
- Assembly costs including tooling costs
- Material
- Direct labor
- Energy
- Equipment
- Building (Facilities)
- Maintenance
- Overhead labor in manufacturing plant, (i.e., indirect labor directly connected to the manufacturing and assembly process)

To account for mark-up in purchased parts costs to the OEM, EDAG applied an additional mark-up rate. For this study, the team considered selling, general, and

21 http://www.worldautosteel.org/Projects/Future-Steel-Vehicle.aspx

22 Nallicheri, N., Clark, J., and Field, F., "An Economic Assessment of Alternative Manufacturing Processes for the Camshaft," SAE Technical Paper 901741, 1990, doi:10.4271/901741.

administrative (SG&A) and profit to determine the final purchased price of the sub-system. Note: SG&A includes allowance for R&D costs.

SG&A mark-up rate is used by the supplier to account for the overhead or non-manufacturing related expenses, and some of the other elements such as:

- Supplier Quality
- Upper Management
- Divisional or corporate headquarters cost (e.g., non-manufacturing facilities, utilities, maintenance etc.)
- Research and development
- Sales
- Human Resources

The SG&A mark-up rate is applied as a percentage of the total estimated manufacturing costs. The default range for this cost analysis ranges between 4-6 % depending on the complexity of the manufacturing technology and the respective sub-system design.

Similar to the SG&A mark-up rate, the profit mark-up rate is also proportional to the complexity of the part design and manufacturing method. It also depends on the availability of suppliers that possess a certain manufacturing technology. The profit mark-up rates tend to increase as the number of suppliers decreases for a certain manufacturing technologies. The profit mark-up ranges selected for this study were based on an assumption of 6% based on historical data available from suppliers and OEMs. Also, all the purchased items analyzed in this study are mature with respect to the manufacturing feasibility and supplier availability.

The TCM approach does not account for any OEM indirect costs. The OEM indirect costs include the costs that are not directly related to the manufacturing and assembly activities such as corporate overhead, marketing, shipping expenses, research and development etc. Discussed in **Section 2.4.1**, the consideration of OEM indirect costs is outside the scope of this analysis.

#### 2.4.2.4 Cost Model Tooling Assumptions

Tooling cost is defined as the cost to buy or build new tools (stamping dies, extrusion dies, holding fixtures, cutting tools etc.) to make a specific product. Any design change made to a component necessitates a manufacturing tooling change in most of the cases. These tooling changes can range from minor design changes (cost neutral or low cost impact) to requiring completely new tool designs (high cost impact). Therefore, most any design change, irrespective of the degree of the change, results in a change in tooling cost.

Although tooling difference existed between the production stock Chevrolet Silverado and mass-reduced pick-up truck, the calculated non-perishable tooling (e.g., stamping dies, extrusion dies, weld fixtures, gauges, etc.) result was cost neutral. Perishable tooling used in welding, riveting and adhesive application is amortized into the piece cost.

#### 2.4.2.4.1 Cost Model General Assumptions

For this study, the cost model was created based on the assumption that the parts are manufactured in a Greenfield facility (or a facility new from the ground up) in the United States. The cost assessment encompassed the raw material (steel, aluminum alloy etc.) entering the plant to the complete vehicles leaving.

Pick-up truck's typical life-cycle has been assumed to be five years, with a mid-life cycle face lift changes. The mid-life cycle face lift changes to the vehicle are usually changes such as interior upgrades that do not involve major design changes. The researchers used an annual production volume of 450,000 with a production life of five years for the cost assessment in order to represent an average high sales volume vehicle. The other general cost model inputs that are typical of a high volume manufacturing facility are summarized in **Table 2.4-3**.

**Table 2.4-3: Cost Model General Assumptions**

| Parameters | Assumptions |
|---|---|
| Cost Model Scope | Manufacturing and Assembly Costs |
| Annual Production Volume | 450,000 parts/year |
| Production Location | USA |
| Production life | 5 years |
| Working days | 240 days/year |
| Number of shifts per day | 2 |
| Hours per shift | 8 hours |
| Unplanned downtime per day | 1 hour |
| Unpaid Breaks per shift | 0.5 hour |
| Annual Available plant time | 3360 hours |
| Annual Paid time | 3600 hours |

### 2.4.2.5 Cost Modeling Process

#### 2.4.2.5.1 Manufacturing Cost Modeling Process

As discussed above, the TCM uses an approach in which each of the elements that contribute to the fabrication cost is estimated individually. The final manufacturing costs is a sum total of all the cost elements. The manufacturing cost assessment methodology is illustrated in **Figure 2.4-11**. The TCM methodology used for the manufacturing cost assessment mainly consists of the following steps:

1) Identify the component to be analyzed for costs and obtain the design data using teardown and reverse engineering for the baseline vehicle parts.

2) Engineering review of the individual parts to determine the following:
    - Raw material
    - Appropriate manufacturing technology required
    - Key operations for manufacturing
    - Key applicable process inputs (equipment type, cycle time, material input etc.)

3) Generate process information sheets for all the key information from engineering review

4) Input the component specific parameters into the Part Cost Model

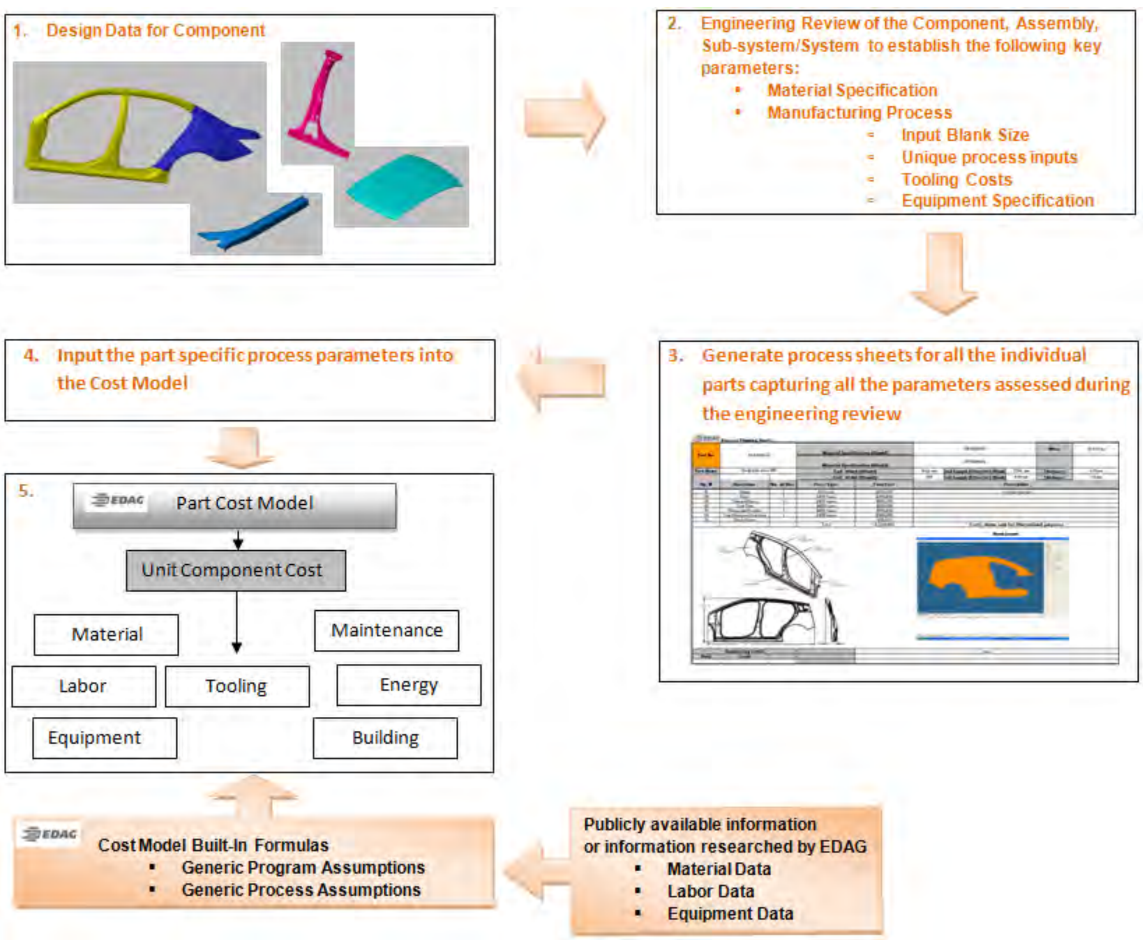


**Figure 2.4-11: Fundamental Steps in Part Manufacturing Cost Assessment**

### 2.4.2.5.2 Assembly Cost Modeling Process

The assembly costs of the body structure and other sub-systems were estimated using a technical cost modeling approach similar to the manufacturing cost assessment methodology explained in above. However, the key parameters for the assembly cost assessment were established based on a detailed engineering review of each individual assembly or sub-assembly.

The assembly cost assessment methodology is illustrated in **Figure 2.4-12**. The TCM methodology used for the assembly cost assessment mainly consists of the following steps:

1) Identify the sub-assemblies/assemblies to be analyzed for the costs and obtain the design data from the vehicle teardown analysis results and CAD data.

2) Engineering review of the sub-assemblies/assemblies to determine the

following:

- Sub-Assembly/Assembly Structure
- Joining Process
- Assembly Process Parameters, for example:
    - Length of weld (Laser Welding, Laser Brazing)
    - Number of welds (Resistance Spot Welding)
    - Number of rivets (Self-Piercing Rivets)
    - Length of bond (Adhesive bonding)
    - Length of hem flange (Hemming)

3) Generate assembly sequence block diagrams sheets for each individual sub-assembly/assembly capturing all the key information from the engineering review

4) Input the sub-assembly/assembly specific parameters into the Assembly Cost Model

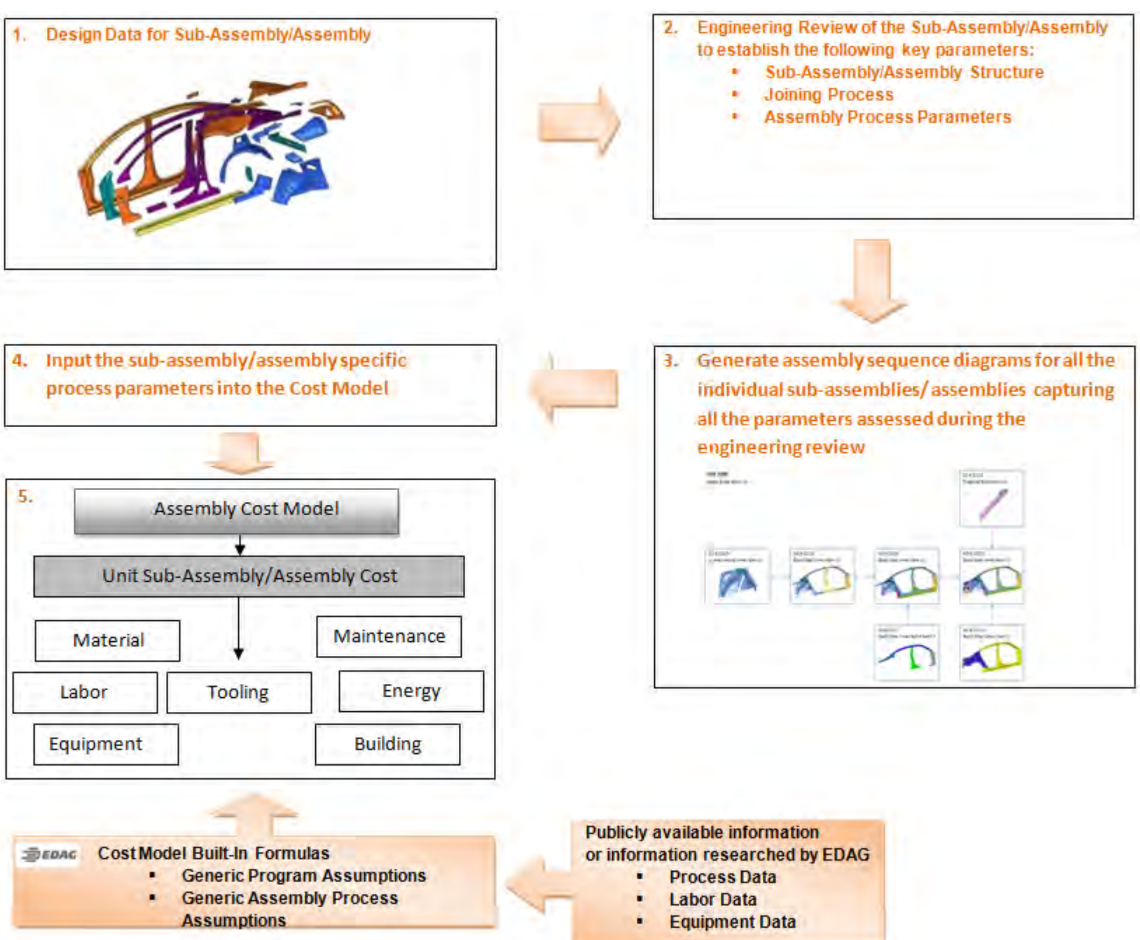


**Figure 2.4-12: Fundamental Steps in Assembly Cost Assessment**

### 2.4.2.5.3 Part Specific Inputs

One of the key steps in the part costs analysis is the determination of the material and the manufacturing technology suitable for producing each respective part. Most significantly, the manufacturing process should be able to produce the part at a high quality, and cost effectively in a high production volume scenario to represent the automotive manufacturing industry. Further, all the parts were also reviewed to establish the following key process input parameters that are unique for every component:

- Input material (Blank size)
- Tooling investment and cycle time
- Equipment specification

### 2.4.2.5.4 Cost Model Generic Process Inputs

The unit manufacturing cost is derived from one of the following cost models based on the selected manufacturing processes:

- Stamping
- Stamping Tailor Rolled Blank (TRB)
- Stamping Laser Welded Blank (LWB)
- Hot Stamping
- Hot Stamping Tailor Rolled Blank
- Hot Stamping Laser Welded Blank
- Closed Rollforming
- Open Rollforming
- Hydroforming
- Hydroforming Laser Welded Tube
- Casting
- Injection Molding
- Self-Piercing Riveting

The unit assembly cost employs one of the following costs models based on the selected assembly processes:

- Resistance Spot welding
- Metal Inert Gas (MIG) welding
- Laser welding

- Laser braze
- Adhesive bonding
- Roller Hemming
- Self-Piercing Riveting

For each of the above mentioned processes, the generic process parameters that are independent of the part/assembly design are built-in as formulas within the cost model. For example, the general stamping press line process parameters are shown in **Table 2.4-4**.

**Table 2.4-4: Stamping Press Line General Process Parameters**

| Process Parameter | Stamping Assumptions |
|---|---|
| Energy consumption rate | 150 kW/hr |
| Space requirement | 150 $m^2$/line |
| Unplanned downtime | 1 hour/day |
| Maintenance Percentage | 10% |
| Material loss percent | 0.5% |
| Press line die average change time | 30 minutes |
| Press line lot size | 1500 parts/lot |

Similar to the process parameters shown in Table 2.4-4, there are generic parameters built into the cost model for each operation required to fabricate or assemble a part using a particular manufacturing or assembly technology. For each operation, the team must consider the sequence of the different operations, to estimate the overall manufacturing component cost for the various technologies as shown in **Table 2.4-5**.

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**Table 2.4-5: Manufacturing Processes and Operations Sequence**

| | Manufacturing Portfolio | | | | | |
|---|---|---|---|---|---|---|
| | Stamping | Stamping Tailor Rolled Blank | Stamping Laser Welded Blank | Hot Stamping | Hot Stamping Laser Welded Blank | Injection Molding |
| Material Price | Steel/Aluminum Material Prices | Steel Material Prices w/ Rolling Premium | Steel Material Prices | Steel Material Prices | Steel Material Prices | Heat Plastic |
| Operation #1 | Blanking (Single) | Blanking | Blanking | Blanking | Blanking | Injection |
| Operation #2 | Stamping | Stamping | Laser Welding | Blank heating | Laser Welding | Mold |
| Operation #3 | Trimming | Trimming | Stamping | Hot forming | Blank heating | Cooling |
| Operation #4 | | | Trimming | Laser | Hot forming | Ejection |
| Operation #5 | | | | | Laser | |

| | Manufacturing Portfolio | | | | | |
|---|---|---|---|---|---|---|
| | Closed Roll Form | Open - Roll Form | Hydroform | Hydroform Laser Welded Tubes (LWT) | Casting | Aluminium Extrusion |
| Material Price | Steel Material Prices | Steel Material Prices | Steel Material Prices w/ Tubing Premium | Steel Material Prices | Magnesium/ Aluminum | Aluminum Material Prices |
| Operation #1 | Forming | Forming | Bending | Blanking | Melting | Cutting Billet |
| Operation #2 | Welding | Trimming | Pre-forming | Laser Welding | Die Casting | Extrusion |
| Operation #3 | Trimming | | Hydroforming | Master | Trimming | Straightening |
| Operation #4 | | | Trimming | Tube | Machining | Hydrosizing |
| Operation #5 | | | | Bending | | Machining |
| Operation #6 | | | | Pre-forming | | |
| Operation #7 | | | | Hydroforming | | |
| Operation #8 | | | | Trimming | | |

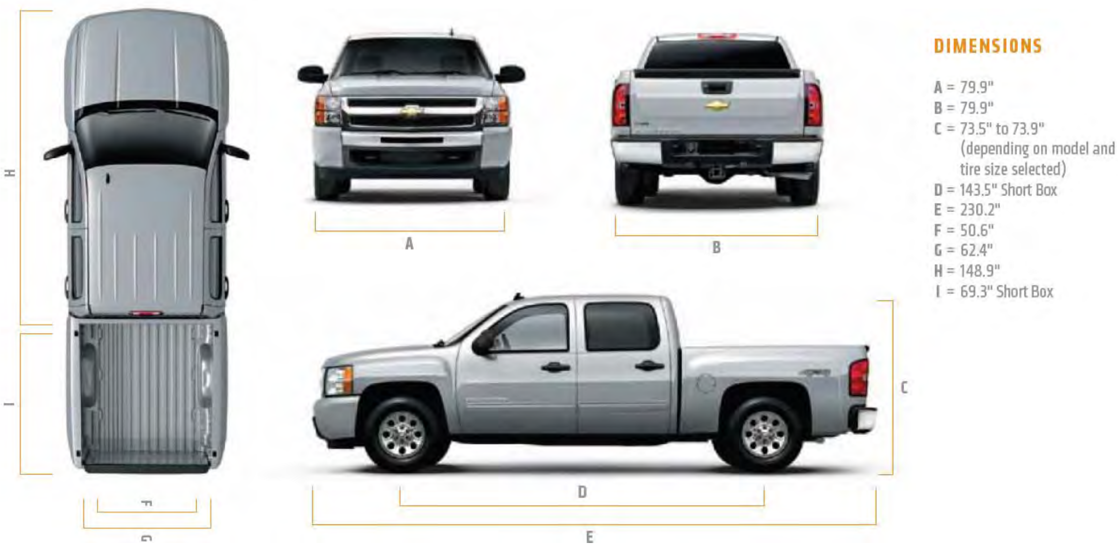
Apart from the generic program assumptions and the generic process parameters, the cost model also uses certain key information for calculating the above mentioned cost components: the information for material prices ($/kg), labor rates ($/hr), equipment investment ($).The material costs also takes into account the scrap rate from each unit operation in the manufacturing process. Energy, building and maintenance are calculated based on each respective generic process parameters. The building costs estimated in the model were apportioned based on the actual space occupied and the specific requirements to manufacture a specific part. Similarly, the maintenance costs in the model is for maintaining the tools, equipment and building and is proportional to the actual utilization for manufacturing and assembly which is also directly linked to the manufacturing process.

Additional details on costing assumptions and parameters used in the analysis for the Body and Frame Evaluation Group can be found in **Appendix Section 7.2.9** (Cost Assumptions). Final body and frame cost analysis results can be found in **Section 4.18**.

# 3. Mass Reduction and Cost Analysis Results Overview

## 3.1 Mass Reduction and Cost Analysis Results Overview – Vehicle Level

The following section provides an overview of the baseline vehicle evaluated, project assumptions, and summary of the mass reduction and cost analysis results.




**Source: 2011 Chevrolet Silverado 1500 Dealership Brochure**

### 3.1.1 Mass Reduction, Cost and Volume Study Assumptions

As stated in the introduction, the foundation of the mass reduction and cost analysis was a 2011 model year Chevrolet Silverado 1500 LT, Crew Cab, Short Box. The evaluated full-size, light-duty 4x4 pick-up truck came equipped with a 5.3 liter, Vortec V8 internal combustion engine and a 6-speed automatic transmission. The vehicle had a 3.42 axle ratio supporting a tow capacity of 4,318 kilograms (9,500lbs) and gross combined vehicle weight (GCVW) of 6818 kilograms (15,000lbs).

The weight of production stock Chevrolet Silverado vehicle, as measured, was 2,386 kg (5,260 lbs.). The curb weight of the vehicle, with a full tank of gas, is calculated to weigh 2,454 kg (5,410 lbs). This was the baseline starting mass for the analysis. **Figure 3.1-1** shows the starting mass for each of the major vehicle systems evaluated.

The purchase price of the vehicle was $36,400. Based on the assumption of a 1.5 times retail price equivalent (RPE), the estimated direct manufacturing cost of the Silverado vehicle was $24,300. The upper boundary condition to the vehicle direct manufacturing costs increase was set at 10% or $2,430.

The 2011/2012 Chevrolet Silverado annual production sales volume range is 415k - 460k units per year (*http://www.goodcarbadcar.net/2011/01/chevroletsilverado-sales-figures.html*). For the overall project, an annual vehicle production volume of 450K units was assumed. In the case of the Chevrolet Silverado, many of the components and assemblies (e.g., engine, transmission brake and other vehicle system components) are cross-platform shared well beyond the 450K units per year (i.e., more than 500K units per year). For the cost portion of the analysis all components were assumed to be manufactured at 450K units/year.

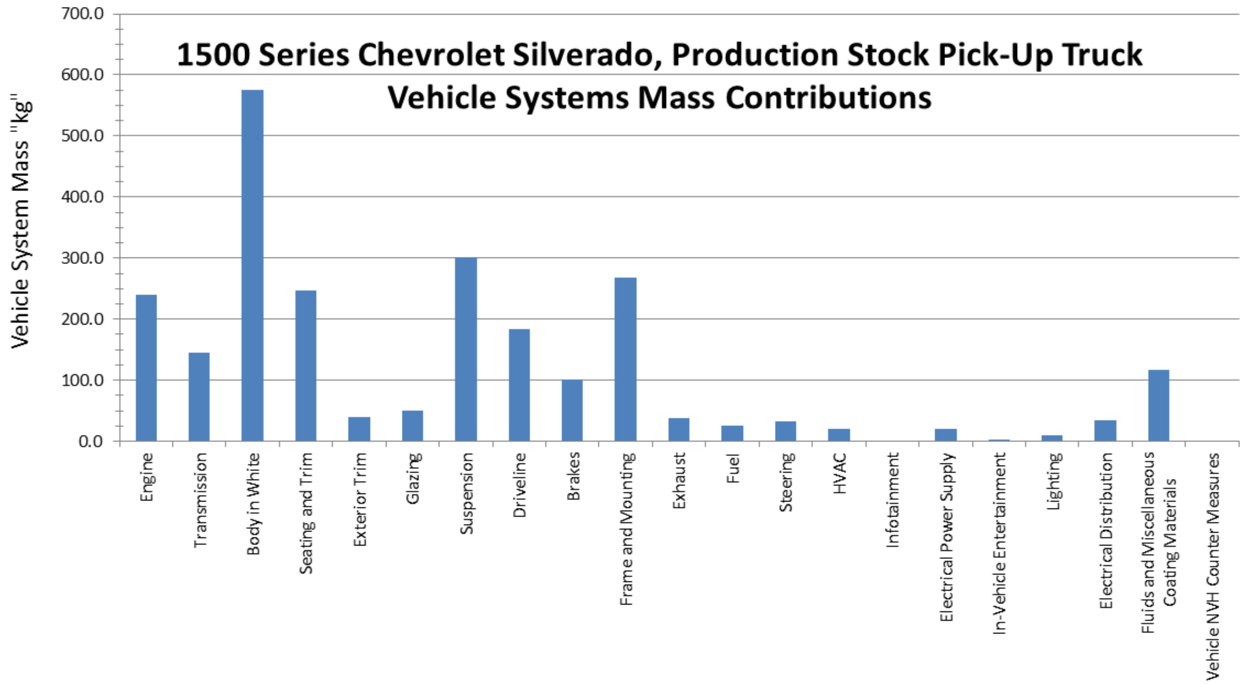



**Figure 3.1-1 Mass of 2011 Chevrolet Silverado (Production Stock) Vehicle Systems**

### 3.1.2 Vehicle Mass Reduction and Cost Summary

The entire vehicle achieved a mass reduction of 560.9 kg (22.9%) at a cost increase of $2,073.82 per vehicle. Including an allowance of 50kg for NVH countermeasures at a cost of $150, the net vehicle mass reduction achieved was 510.9 kg (20.8%) at a cost increase of $2,223.82. This equals an average cost per kilogram, inclusive of the NVH counter measures, of $4.35 per kg.

The NVH mass and cost countermeasure values incorporated into the analysis are budgetary estimates based on engineering experience. No full vehicle NVH analysis work was completed to develop system/subsystem/assembly counter-measures as part this project.

The major mass saving systems in the Chevrolet Silverado include: Body system (Group -A-), which saved 8.4% of the vehicle weight; the Suspension system, 4.3%; and the Brake system, 1.9%. The Engine and Transmission systems reduced the vehicle mass by

1.3% and 1.6% respectively. **Figure 3.1-2** presents the starting mass for each of the baseline vehicle systems along with final mass of each system evaluated.

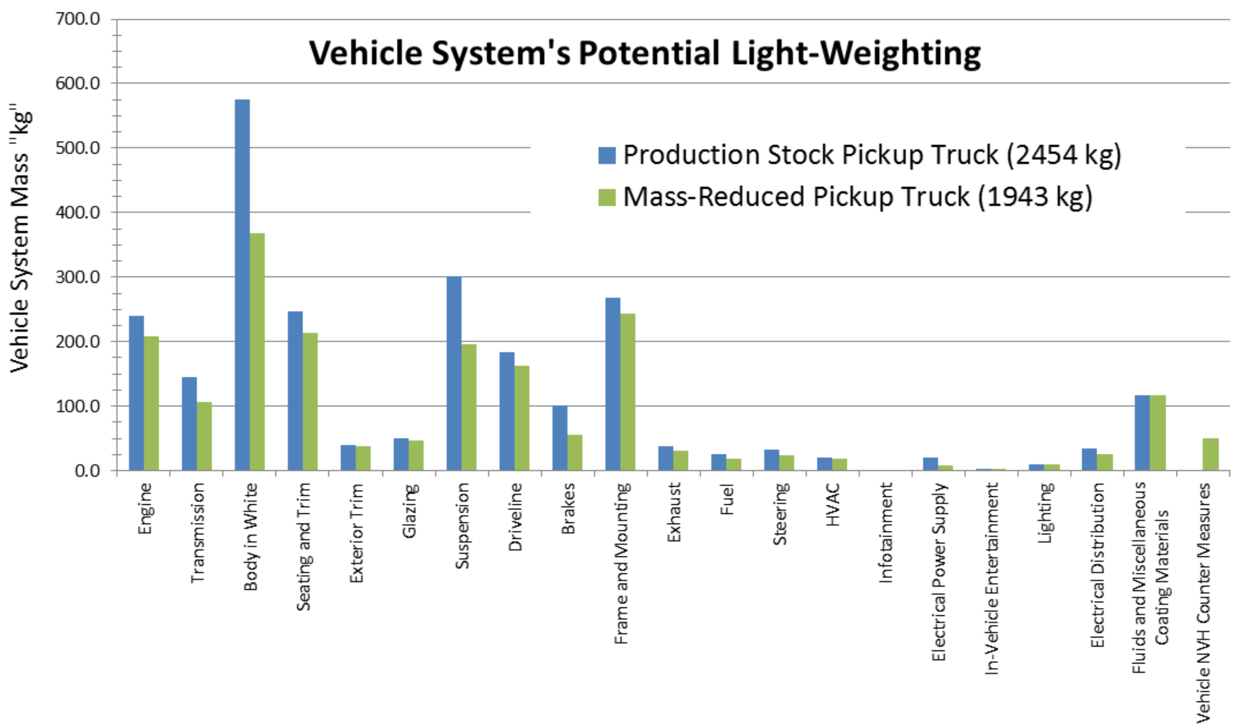



**Figure 3.1-2: Calculated System Mass Reduction Relative to Baseline Vehicle Starting Mass**

**Table 3.1-1** is the vehicle mass reduction summary, including the mass reduction and cost impact from each of the major vehicle systems and subsystems evaluated. The cost per kilogram for weight reduction in each system and subsystem are summarized with and without tooling. For systems/subsystems which have a cost increase associated with mass reduction [i.e., negative value ($/kg)], a larger negative number indicated a tooling increase with mass reduction. Conversely a smaller negative number represents a decrease in tooling. For systems/subsystems which experienced a unit cost savings with mass reduction (i.e., positive value $/kg), a larger number represents a tooling decrease with mass reduction. In both scenarios, no difference in the cost per kilogram value, with and without tooling, indicates the associated tooling modifications were estimated to be cost neutral.

**Table 3.1-1: System/Subsystem Mass Reduction and Cost Analysis Summary**

| System | Subsystem | Sub-Subsystem | Description | Baseline System/ Subsystem Mass "kg" | Mass Reduction "+" Mass Decrease "-" Mass Increase "kg" | % Vehicle Mass Reduction | NIDMC/ Kilogram (w/o Tooling) "+" Mass Decrease "-" Mass Increase "$/kg" | NIDMC/ Kilogram (w/ Tooling) "+" Mass Decrease "-" Mass Increase "$/kg" |
|---|---|---|---|---|---|---|---|---|
| 01 | 00 | 00 | Engine System | 239.95 | 31.84 | 1.33% | (2.92) | (2.63) |
| 01 | 02 | 00 | Engine Frames, Mounting, and Brackets Subsystem | 6.07 | 1.45 | 0.06% | 0.39 | 0.31 |
| 01 | 03 | 00 | Crank Drive Subsystem | 37.00 | 4.49 | 0.19% | 1.57 | 1.51 |
| 01 | 05 | 00 | Cylinder Block Subsystem | 59.86 | 6.36 | 0.27% | 1.60 | 1.68 |
| 01 | 06 | 00 | Cylinder Head Subsystem | 24.90 | 2.37 | 0.10% | 4.11 | 5.62 |
| 01 | 07 | 00 | Valvetrain Subsystem | 16.26 | 0.32 | 0.01% | 1.57 | 0.09 |
| 01 | 08 | 00 | Timing Drive Subsystem | 1.75 | 0.42 | 0.02% | (5.88) | (3.93) |
| 01 | 09 | 00 | Accessory Drive Subsystem | 8.27 | 2.06 | 0.09% | 0.35 | 0.01 |
| 01 | 10 | 00 | Air Intake Subsystem | 11.95 | 0.94 | 0.04% | (0.58) | (0.50) |
| 01 | 11 | 00 | Fuel Induction Subsystem | 1.12 | 0.00 | 0.00% | 0.00 | 0.00 |
| 01 | 12 | 00 | Exhaust Subsystem | 12.17 | 3.43 | 0.14% | (5.56) | (5.56) |
| 01 | 13 | 00 | Lubrication Subsystem | 10.55 | 3.12 | 0.13% | (3.42) | (3.32) |
| 01 | 14 | 00 | Cooling Subsystem | 24.32 | 3.77 | 0.16% | (23.85) | (22.71) |
| 01 | 16 | 00 | Exhaust Gas Re-circulation Subsystem | 0.05 | 0.00 | 0.00% | 0.00 | 0.00 |
| 01 | 17 | 00 | Breather Subsystem | 0.11 | 0.00 | 0.00% | 0.00 | 0.00 |
| 01 | 60 | 00 | Engine Management, Engine Electronic, Electrical Subsystem | 5.67 | 0.89 | 0.04% | 2.23 | 2.61 |
| 01 | 70 | 00 | Accessory Subsystems (Start Motor, Generator, etc.) | 19.89 | 2.23 | 0.09% | (0.40) | (0.06) |
| | | | | | | | | |
| 02 | 00 | 00 | Transmission System | 145.28 | 39.35 | 1.20% | (2.45) | (2.47) |
| 02 | 01 | 00 | External Components | 0.02 | 0.00 | 0.00% | 0.00 | 0.00 |
| 02 | 02 | 00 | Case Subsystem | 30.73 | 11.93 | 0.36% | (2.14) | (2.01) |
| 02 | 03 | 00 | Gear Train Subsystem | 12.39 | 2.70 | 0.08% | 9.84 | 9.82 |
| 02 | 04 | 00 | Internal Clutch Subsystem | 30.47 | 5.41 | 0.16% | (5.80) | (5.80) |
| 02 | 05 | 00 | Launch Clutch Subsystem | 20.29 | 9.75 | 0.30% | (1.98) | (2.21) |
| 02 | 06 | 00 | Oil Pump and Filter Subsystem | 7.50 | 2.46 | 0.07% | (3.95) | (4.08) |
| 02 | 07 | 00 | Mechanical Controls Subsystem | 7.14 | 1.02 | 0.03% | (3.29) | (2.86) |
| 02 | 08 | 00 | Electrical Controls Subsystem | 4.30 | 0.00 | 0.00% | 0.00 | 0.00 |
| 02 | 09 | 00 | Parking Mechanism Subsystem | 0.88 | 0.06 | 0.00% | 86.61 | 86.61 |
| 02 | 12 | 00 | Transfer Case Subsystem | 28.44 | 6.01 | 0.18% | (6.55) | (6.54) |
| 02 | 20 | 00 | Driver Operated External Controls Subsystem | 3.13 | 0.00 | 0.00% | 0.00 | 0.00 |
| | | | | | | | | |
| 03 | 00 | 00 | Body System Group -A- ( Body Sheetmetal) | 574.72 | 207.10 | 8.44% | (5.77) | (5.77) |
| 03 | 01 | 00 | Body Structure Subsystem | 207.20 | 75.40 | 3.16% | (6.72) | (6.72) |
| 03 | 02 | 00 | Front End | 38.32 | 12.30 | 0.52% | (5.05) | (5.05) |
| 03 | 03 | 00 | Body Closure Subsystem | 153.70 | 60.00 | 2.51% | (4.82) | (4.82) |
| 03 | 04 | 00 | Second Unit Body | 0.00 | 0.00 | 0.00% | 0.00 | 0.00 |
| 03 | 18 | 00 | Body Paint | 0.00 | 0.00 | 0.00% | 0.00 | 0.00 |
| 03 | 19 | 00 | Bumpers Subsystem | 48.40 | 16.40 | 4.29% | (4.25) | (4.25) |
| 03 | 26 | 00 | Pickup Box | 127.10 | 43.00 | 1.80% | (6.22) | (6.22) |
| | | | | | | | | |
| 03 | 00 | 00 | Body System Group -B- (Body Interior) | 247.02 | 34.02 | 1.25% | (3.74) | (3.78) |
| 03 | 05 | 00 | Interior Trim and Ornamentation Subsystem | 56.545 | 2.06 | 0.09% | 3.32 | 3.32 |
| 03 | 06 | 00 | Sound and Heat Control Subsystem (Body) | 4.78 | 0.00 | 0.00% | 0.00 | 0.00 |
| 03 | 07 | 00 | Sealing Subsystem | 14.52 | 4.72 | 0.20% | 6.84 | 6.84 |
| 03 | 10 | 00 | Seating Subsystem | 120.69 | 19.16 | 0.63% | (6.68) | (6.85) |
| 03 | 12 | 00 | Instrument Panel and Console Subsystem | 30.84 | 6.82 | 0.28% | (5.17) | (5.06) |
| 03 | 20 | 00 | Occupant Restraining Device Subsystem | 19.64 | 1.26 | 0.05% | (2.47) | (1.62) |
| | | | | | | | | |
| 03 | 00 | 00 | Body System Group -C- (Body Exterior Trim) | 40.47 | 2.14 | 0.09% | 1.28 | 1.28 |
| 03 | 08 | 00 | Exterior Trim and Ornamentation Subsystem | 12.82 | 0.99 | 0.04% | 1.06 | 1.06 |
| 03 | 09 | 00 | Rear View Mirrors Subsystem | 4.26 | 0.37 | 0.02% | 2.51 | 2.51 |
| 03 | 23 | 00 | Front End Modules | 21.08 | 0.57 | 0.02% | 0.87 | 0.87 |
| 03 | 24 | 00 | Rear End Modules | 2.30 | 0.20 | 0.01% | 1.20 | 1.20 |
| | | | | | | | | |
| 03 | 00 | 00 | Body System Group -D- (Glazing & Body Mechatronics) | 50.86 | 4.50 | 0.19% | 0.51 | 0.51 |
| 03 | 11 | 00 | Glass (Glazing), Frame and Mechanism Subsystem | 39.60 | 4.43 | 0.19% | 0.50 | 0.50 |
| 03 | 14 | 00 | Handles, Locks, Latches and Mechanisms Subsystem | 5.66 | 0.00 | 0.00% | 0.00 | 0.00 |
| 03 | 16 | 00 | Wipers and Washers Subsystem | 5.61 | 0.07 | 0.00% | 0.84 | 0.84 |
| | | | | | | | | |
| 04 | 00 | 00 | Suspension System | 301.24 | 105.42 | 4.42% | (1.47) | (1.48) |
| 04 | 01 | 00 | Front Suspension Subsystem | 54.76 | 23.75 | 1.00% | (0.57) | (0.60) |
| 04 | 02 | 00 | Rear Suspension Subsystem | 63.52 | 38.41 | 1.61% | (2.19) | (2.19) |
| 04 | 03 | 00 | Shock Absorber Subsystem | 24.36 | 7.14 | 0.30% | (0.12) | (0.13) |
| 04 | 04 | 00 | Wheels And Tires Subsystem | 158.61 | 36.12 | 1.51% | (1.56) | (1.56) |

**Table 3.1-1: System/Subsystem Mass Reduction and Cost Analysis Summary (Cont'd)**

| System | Subsystem | Sub-Subsystem | Description | Baseline System/ Subsystem Mass "kg" | Mass Reduction "+" Mass Decrease "-" Mass Increase "kg" | % Vehicle Mass Reduction | NIDMC/ Kilogram (w/o Tooling) "+" Mass Decrease "-" Mass Increase "$/kg" | NIDMC/ Kilogram (w/ Tooling) "+" Mass Decrease "-" Mass Increase "$/kg" |
|---|---|---|---|---|---|---|---|---|
| 05 | 00 | 00 | Driveline System | 183.82 | 20.42 | 0.86% | 1.86 | 1.89 |
| 05 | 01 | 00 | Driveshaft Subsystem | 14.31 | 2.10 | 0.09% | 1.61 | 1.61 |
| 05 | 02 | 00 | Rear Drive Housed Axle Subsystem | 89.07 | 10.47 | 0.44% | 2.46 | 2.48 |
| 05 | 03 | 00 | Front Drive Housed Axle Subsystem | 52.53 | 6.49 | 0.27% | 0.97 | 1.02 |
| 05 | 04 | 00 | Front Drive Half-Shafts Subsystem | 27.62 | 1.36 | 0.06% | 1.90 | 1.90 |
| 05 | 07 | 00 | 4WD Driveline Control Subsystem | 0.29 | 0.00 | 0.00% | 0.00 | 0.00 |
| | | | | | | | | |
| 06 | 00 | 00 | Brake System | 101.01 | 45.83 | 1.92% | (3.25) | (3.35) |
| 06 | 03 | 00 | Front Rotor/Drum and Shield Subsystem | 42.98 | 23.06 | 0.97% | (1.97) | (2.02) |
| 06 | 04 | 00 | Rear Rotor/Drum and Shield Subsystem | 34.26 | 17.20 | 0.72% | (3.66) | (3.69) |
| 06 | 05 | 00 | Parking Brake and Actuation Subsystem | 4.70 | 1.45 | 0.06% | (10.72) | (11.44) |
| 06 | 06 | 00 | Brake Actuation Subsystem | 10.66 | 2.53 | 0.11% | (0.18) | (0.59) |
| 06 | 07 | 00 | Power Brake Subsystem (for Hydraulic) | 4.24 | 1.58 | 0.07% | (15.57) | (16.10) |
| 06 | 09 | 00 | Brake Controls Subsystem | 4.17 | 0.00 | 0.00% | 0.00 | 0.00 |
| | | | | | | | | |
| 07 | 00 | 00 | Frame and Mounting System | 267.63 | 23.70 | 0.99% | (2.30) | (2.30) |
| 07 | 01 | 00 | Frame Sub System | 252.27 | 23.70 | 0.99% | (2.30) | (2.30) |
| 07 | 03 | 00 | Engine Transmission Mounting Subsystem | 2.14 | 0.00 | 0.00% | 0.00 | 0.00 |
| 07 | 04 | 00 | Towing and Coupling Attachments Subsystem | 13.23 | 0.00 | 0.00% | 0.00 | 0.00 |
| | | | | | | | | |
| 09 | 00 | 00 | Exhaust System | 38.37 | 6.95 | 0.29% | (1.97) | (1.97) |
| 09 | 01 | 00 | Acoustical Control Components Subsystem | 38.37 | 6.95 | 0.29% | (1.97) | (1.97) |
| | | | | | | | | |
| 10 | 00 | 00 | Fuel System | 26.34 | 7.34 | 0.31% | 1.62 | 1.77 |
| 10 | 01 | 00 | Fuel Tank And Lines Subsystem | 22.60 | 6.46 | 0.27% | 1.71 | 1.86 |
| 10 | 02 | 00 | Fuel Vapor Management Subsystem | 3.74 | 0.88 | 0.04% | 1.02 | 1.16 |
| | | | | | | | | |
| 11 | 00 | 00 | Steering System | 32.51 | 8.46 | 0.33% | (17.44) | (17.45) |
| 11 | 01 | 00 | Steering Gear Subsystem | 13.89 | (1.47) | -0.06% | 168.57 | 168.57 |
| 11 | 02 | 00 | Power Steering Pump | 5.44 | 5.44 | 0.23% | 7.48 | 7.48 |
| 11 | 03 | 00 | Steering Column Subsystem | 1.01 | 1.01 | 0.03% | 53.73 | 53.73 |
| 11 | 04 | 00 | Steering Column Switches Subsystem | 12.17 | 3.47 | 0.14% | 1.37 | 1.33 |
| | | | | | | | | |
| 12 | 00 | 00 | Climate Control System | 20.31 | 1.94 | 0.08% | 7.59 | 7.59 |
| 12 | 01 | 00 | Air Handling/Body Ventilation Subsystem | 14.88 | 1.94 | 0.08% | 7.59 | 7.59 |
| 12 | 02 | 00 | Heating/Defrosting Subsystem | 0.29 | 0.00 | 0.00% | 0.00 | 0.00 |
| 12 | 03 | 00 | Refrigeration/Air Conditioning Subsystem | 4.74 | 0.00 | 0.00% | 0.00 | 0.00 |
| 12 | 04 | 00 | Controls Subsystem | 0.39 | 0.00 | 0.00% | 0.00 | 0.00 |
| | | | | | | | | |
| 13 | 00 | 00 | Information, Gage and Warning Device System | 1.58 | 0.25 | 0.01% | 2.66 | 2.97 |
| 13 | 01 | 00 | Instrument Cluster Subsystem | 1.06 | 0.06 | 0.00% | 7.67 | 7.67 |
| 13 | 06 | 00 | Horn Subsystem | 0.52 | 0.18 | 0.01% | 0.93 | 1.35 |
| | | | | | | | | |
| 14 | 00 | 00 | Electrical Power Supply System | 21.12 | 12.81 | 0.52% | (13.49) | (13.44) |
| 14 | 01 | 00 | Service Battery Subsystem | 21.12 | 12.81 | 0.54% | (13.49) | (13.44) |
| | | | | | | | | |
| 15 | 00 | 00 | In-Vehicle Entertainment System | 2.22 | 0.00 | 0.00% | 0.00 | 0.00 |
| 15 | 01 | 00 | Receiver and Audio Media Subsystem | 1.72 | 0.00 | 0.00% | 0.00 | 0.00 |
| 15 | 02 | 00 | Antenna Subsystem | 0.50 | 0.00 | 0.00% | 0.00 | 0.00 |
| | | | | | | | | |
| 17 | 00 | 00 | Lighting System | 9.56 | 0.39 | 0.02% | (5.18) | (5.18) |
| 17 | 01 | 00 | Front Lighting Subsystem | 6.70 | 0.39 | 0.02% | (5.18) | (5.18) |
| 17 | 03 | 00 | Rear Lighting Subsystem | 2.74 | 0.00 | 0.00% | 0.00 | 0.00 |
| 17 | 05 | 00 | Lighting Switches Subsystem | 0.13 | 0.00 | 0.00% | 0.00 | 0.00 |
| | | | | | | | | |
| 18 | 00 | 00 | Electrical Distribution and Electronic Control System | 33.59 | 8.47 | 0.35% | 7.26 | 7.27 |
| 18 | 01 | 00 | Electrical Wiring and Circuit Protection Subsystem | 33.59 | 8.47 | 0.35% | 7.26 | 7.27 |

In the vehicle level Cost Model Analysis Template (CMAT) (**Table 3.1-2 - Table 3.1-4**), the cost elements that generate the NIDMCs at a vehicle system level are presented. The costs, captured only for vehicle differences having an overall positive or negative cost impact, are broken out for each of the major systems. As mentioned previously, incremental costs are calculated by subtracting the new (i.e., mass reduced) component costs from the baseline component costs. Thus a negative incremental cost indicates a price increase of the mass-reduced technology over the baseline technology.

From the cost element breakdown within the table, the NIDMC shows an overall vehicle increase of $2,074 The material cost increase is $1,570 while the labor and manufacturing overhead costs increased to $139 and $263, respectively. The resulting total manufacturing cost (TMC) was an increase of $1,972. Adding the total mark-up cost of $102 associated with the TMC results in a NIDMC increase of $2,074. The NVH counter measure costs are added to the final NIDMC as a lump sum estimate and are not included in the CMAT values.

Also provided in the CMAT tables are the costs for the incremental tooling for the baseline and mass-reduced Silverado vehicle. The incremental tooling expense for the mass-reduced Silverado is approximately $7.3M less than the baseline Silverado.

**Table 3.1-2: Vehicle Level Cost Model Analysis Templates (CMAT): Baseline**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | BASE TECHNOLOGY GENERAL PART INFORMATION: | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | System | Name/Description | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| 1 | 01 Engine | | 137.47 | 21.96 | 100.72 | 260.16 | 6.54 | 22.27 | 19.26 | 5.14 | 53.21 | - | 313.36 | - | 30,953.62 | - |
| 2 | 02 Transmission | | 325.40 | 65.27 | 119.24 | 509.91 | 3.98 | 39.82 | 41.31 | 16.01 | 101.12 | - | 611.03 | - | 21,835.00 | - |
| 3 | 03 Body | | 1,492.27 | 96.29 | 274.74 | 1,863.29 | 2.79 | 41.38 | 34.41 | 9.05 | 87.62 | - | 1,950.91 | - | 16,958.33 | - |
| | | Body System Group -A- ( Body Sheetmetal) | 1,149.08 | 36.29 | 108.39 | 1,293.76 | 0.11 | 1.40 | 1.29 | 0.38 | 1,296.94 | - | 1,296.94 | - | - | - |
| | | Body System Group -B- (Body Interior) | 278.23 | 54.79 | 80.90 | 413.92 | 1.91 | 30.50 | 23.95 | 5.23 | 475.51 | - | 475.51 | - | 16.958 | - |
| | | Body System Group -C- (Body Exterior Trim) | 49.53 | 1.89 | 3.59 | 55.02 | 0.30 | 4.75 | 3.77 | 0.76 | 64.60 | - | 64.60 | - | - | - |
| | | Body System Group -D- (Glazing & Body Mechatronics) | 15.43 | 3.31 | 81.85 | 100.59 | 0.47 | 4.74 | 5.40 | 2.68 | 113.87 | - | 113.87 | - | - | - |
| 4 | 04 Suspension | | 608.17 | 83.72 | 242.96 | 934.85 | 4.71 | 46.24 | 51.70 | 24.98 | 127.63 | - | 1,062.49 | - | 8,598.92 | - |
| 5 | 05 Driveline | | 168.70 | 32.36 | 104.45 | 305.52 | 3.13 | 26.48 | 25.05 | 7.85 | 62.51 | - | 368.03 | - | 1,431.25 | - |
| 6 | 06 Brakes | | 132.86 | 21.22 | 85.60 | 239.68 | 1.29 | 14.75 | 15.11 | 6.60 | 37.75 | - | 277.43 | - | 10,345.86 | - |
| 7 | 07 Frame and Mounting | | 479.02 | - | - | 479.02 | - | - | - | - | - | - | 479.02 | - | - | - |
| 8 | 09 Exhaust | | 31.13 | 1.67 | 4.32 | 37.12 | 0.24 | 3.24 | 2.91 | 0.85 | 7.24 | - | 44.35 | - | - | - |
| 9 | 10 Fuel | | 131.07 | 3.13 | 19.16 | 153.36 | 0.54 | 7.58 | 6.58 | 2.37 | 17.07 | - | 170.43 | - | 3,004.25 | - |
| 10 | 11 Steering | | 151.24 | 38.50 | 47.54 | 237.27 | 2.32 | 20.72 | 23.12 | 12.88 | 59.04 | - | 296.32 | - | 2,366.50 | - |
| 11 | 12 Climate Control | | 17.91 | 3.84 | 20.23 | 41.98 | 0.32 | 3.86 | 3.83 | 1.30 | 9.31 | - | 51.29 | - | - | - |
| 12 | 13 Info, Gage & Warning Device | | 2.77 | 0.54 | 1.77 | 5.08 | 0.03 | 0.44 | 0.34 | 0.07 | 0.87 | - | 5.96 | - | 519.90 | - |
| 13 | 14 Electrical Power Supply | | 23.21 | 6.51 | 6.51 | 36.23 | 0.10 | 1.66 | 1.23 | 0.35 | 3.33 | - | 39.56 | - | 1,429.57 | - |
| 14 | 15 In-Vehicle Entertainment | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 15 | 17 Lighting | | 6.36 | 1.15 | 2.80 | 10.31 | 0.05 | 0.48 | 0.55 | 0.27 | 1.34 | - | 11.65 | - | - | - |
| 16 | 18 Electrical Distribution & Electrical Control | | 95.83 | 0.67 | 1.13 | 97.63 | 0.41 | 8.03 | 5.41 | 0.72 | 14.57 | - | 112.20 | - | 318.50 | - |
| 17 | 19 Electronic Features | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | SUBSYSTEM ROLL-UP | | 3,803.41 | 376.83 | 1,031.17 | 5,211.41 | 26.44 | 236.94 | 230.80 | 88.43 | 582.61 | - | 5,794.02 | - | 97,761.69 | - |

**Table 3.1-3: Vehicle Level Cost Model Analysis Templates (CMAT): Mass-Reduced**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | System | Name/Description | Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| 1 | | 01 Engine | 196.46 | 50.66 | 108.32 | 355.44 | 4.62 | 20.53 | 19.72 | 6.85 | 51.72 | - | 407.16 | - | 13,989.61 | - |
| 2 | | 02 Transmission | 395.10 | 61.15 | 125.37 | 583.64 | 6.17 | 48.63 | 50.17 | 18.99 | 123.95 | - | 707.60 | - | 22,932.15 | - |
| 3 | | 03 Body | 2,649.80 | 127.00 | 400.22 | 3,177.02 | 2.86 | 43.82 | 35.59 | 9.52 | 91.79 | - | 3,267.90 | - | 19,663.00 | - |
| | | Body System Group -A- ( Body Sheetmetal) | 2,207.45 | 70.43 | 210.83 | 2,488.70 | 0.10 | 1.33 | 1.23 | 0.36 | 3.02 | - | 2,491.73 | - | - | - |
| | | Body System Group -B- (Body Interior) | 381.05 | 50.71 | 104.40 | 536.16 | 2.01 | 33.30 | 25.47 | 5.81 | 66.58 | - | 602.74 | - | 19,663 | - |
| | | Body System Group -C- (Body Exterior Trim) | 47.89 | 1.65 | 3.15 | 52.69 | 0.29 | 4.55 | 3.61 | 0.73 | 9.18 | - | 61.86 | - | - | - |
| | | Body System Group -D- (Glazing & Body Mechatronics) | 13.42 | 4.21 | 81.84 | 99.47 | 0.46 | 4.64 | 5.29 | 2.62 | 13.01 | - | 111.57 | - | - | - |
| 4 | | 04 Suspension | 678.70 | 101.88 | 292.23 | 1,072.82 | 5.51 | 52.08 | 58.46 | 28.53 | 144.57 | - | 1,217.39 | - | 9,970.45 | - |
| 5 | | 05 Driveline | 126.36 | 38.71 | 110.22 | 275.28 | 1.86 | 23.65 | 22.17 | 7.07 | 54.74 | - | 330.01 | - | 409.10 | - |
| 6 | | 06 Brakes | 237.75 | 26.10 | 99.69 | 363.54 | 3.49 | 22.91 | 25.08 | 11.33 | 62.81 | - | 426.35 | - | 19,210.04 | - |
| 7 | | 07 Frame and Mounting | 533.44 | - | - | 533.44 | - | - | - | - | - | - | 533.44 | - | - | - |
| 8 | | 09 Exhaust | 44.45 | 0.61 | 3.26 | 48.31 | 0.32 | 4.43 | 3.89 | 1.09 | 9.73 | - | 58.04 | - | - | - |
| 9 | | 10 Fuel | 121.50 | 2.91 | 18.15 | 142.57 | 0.51 | 7.02 | 6.17 | 2.25 | 15.94 | - | 158.51 | - | 1,005.70 | - |
| 10 | | 11 Steering | 201.50 | 67.30 | 77.53 | 346.32 | 3.64 | 33.56 | 37.90 | 22.37 | 97.46 | - | 443.78 | - | 2,620.50 | - |
| 11 | | 12 Climate Control | 14.41 | 4.32 | 10.93 | 29.67 | 0.25 | 2.77 | 2.86 | 1.04 | 6.91 | - | 36.58 | - | - | - |
| 12 | | 13 Info, Gage & Warning Device | 2.54 | 0.53 | 1.43 | 4.51 | 0.02 | 0.39 | 0.31 | 0.06 | 0.79 | - | 5.30 | - | 376.10 | - |
| 13 | | 14 Electrical Power Supply | 119.32 | 37.92 | 39.03 | 196.27 | 0.44 | 8.24 | 5.79 | 1.55 | 16.02 | - | 212.29 | - | 243.62 | - |
| 14 | | 15 In-Vehicle Entertainment | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 15 | | 17 Lighting | 9.43 | 0.61 | 2.04 | 12.08 | 0.06 | 0.56 | 0.64 | 0.32 | 1.57 | - | 13.65 | - | - | - |
| 16 | | 18 Electrical Distribution & Electrical Control | 42.28 | (4.33) | 6.14 | 44.09 | 0.19 | 3.64 | 2.49 | 0.35 | 6.66 | - | 50.75 | - | 90.13 | - |
| 17 | | 19 Electronic Features | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | SUBSYSTEM ROLL-UP | 5,373.05 | 515.38 | 1,294.54 | 7,184.99 | 29.93 | 272.22 | 271.23 | 111.30 | 684.67 | - | 7,868.74 | - | 90,510.38 | - |

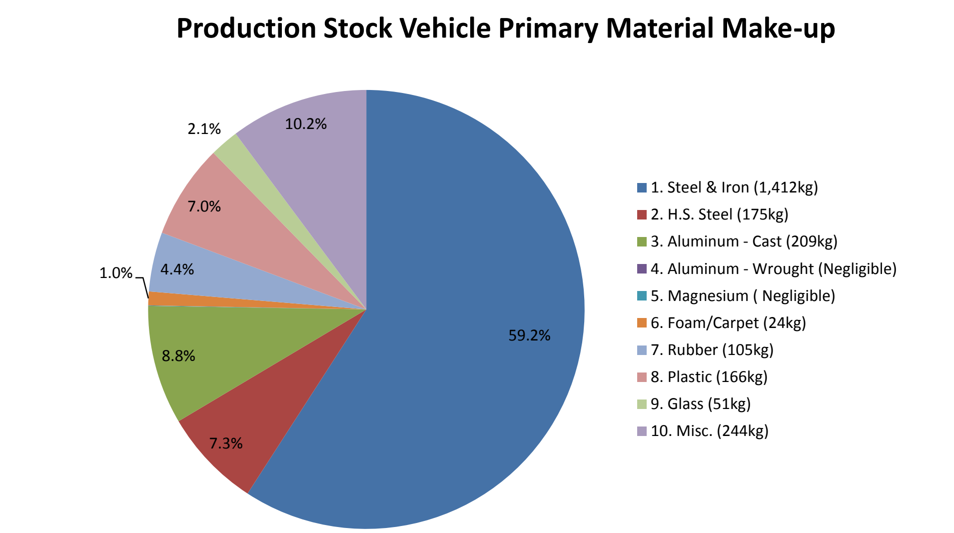
**Table 3.1-4: Vehicle Level Cost Model Analysis Templates (CMAT): Differential**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| 1 | 01 Engine | | (58.99) | (28.70) | (7.59) | (95.29) | 1.92 | 1.74 | (0.48) | (1.71) | 1.49 | - | (93.80) | - | 16,964.01 | - |
| 2 | 02 Transmission | | (69.70) | 4.11 | (8.13) | (73.73) | (2.19) | (3.81) | (8.86) | (2.98) | (22.83) | - | (96.57) | - | (1,097.15) | - |
| 3 | 03 Body | | (1,157.53) | (30.72) | (125.48) | (1,313.73) | (0.08) | (2.44) | (1.18) | (0.47) | (4.17) | - | (1,316.99) | - | (2,704.67) | - |
| | | Body System Group -A- ( Body Sheetmetal) | (1,058.36) | (34.14) | (102.44) | (1,194.94) | 0.01 | 0.06 | 0.06 | 0.02 | 1,293.92 | - | (1,194.79) | - | - | - |
| | | Body System Group -B- (Body Interior) | (102.81) | 4.08 | (23.50) | (122.23) | (0.10) | (2.80) | (1.51) | (0.58) | 408.93 | - | (127.23) | - | (2,705) | - |
| | | Body System Group -C- (Body Exterior Trim) | 1.64 | 0.24 | 0.45 | 2.33 | 0.01 | 0.20 | 0.16 | 0.03 | 55.42 | - | 2.73 | - | - | - |
| | | Body System Group -D- (Glazing & Body Mechatronics) | 2.01 | (0.90) | 0.01 | 1.12 | 0.01 | 0.10 | 0.11 | 0.05 | 100.86 | - | 2.30 | - | - | - |
| 4 | 04 Suspension | | (70.53) | (18.16) | (49.27) | (137.96) | (0.80) | (5.84) | (6.75) | (3.55) | (16.94) | - | (154.90) | - | (1,371.54) | - |
| 5 | 05 Driveline | | 42.34 | (6.34) | (5.76) | 30.23 | 1.27 | 2.84 | 2.88 | 0.78 | 7.77 | - | 38.01 | - | 1,022.15 | - |
| 6 | 06 Brakes | | (104.90) | (4.87) | (14.09) | (123.86) | (2.20) | (8.16) | (9.97) | (4.73) | (25.06) | - | (148.92) | - | (8,864.18) | - |
| 7 | 07 Frame and Mounting | | (54.42) | - | - | (54.42) | - | - | - | - | - | - | (54.42) | - | - | - |
| 8 | 09 Exhaust | | (13.32) | 1.06 | 1.06 | (11.19) | (0.08) | (1.19) | (0.98) | (0.24) | (2.49) | - | (13.69) | - | - | - |
| 9 | 10 Fuel | | 9.57 | 0.22 | 1.01 | 10.80 | 0.03 | 0.56 | 0.41 | 0.12 | 1.12 | - | 11.92 | - | 1,998.55 | - |
| 10 | 11 Steering | | (80.25) | (28.80) | (29.99) | (109.05) | (1.32) | (12.85) | (14.77) | (9.49) | (38.42) | - | (147.46) | - | (254.00) | - |
| 11 | 12 Climate Control | | 3.50 | (0.49) | 9.30 | 12.31 | 0.08 | 1.09 | 0.96 | 0.26 | 2.40 | - | 14.71 | - | - | - |
| 12 | 13 Info, Gage & Warning Device | | 0.23 | 0.01 | 0.34 | 0.57 | 0.00 | 0.05 | 0.03 | 0.00 | 0.09 | - | 0.66 | - | 143.80 | - |
| 13 | 14 Electrical Power Supply | | (96.12) | (31.40) | (32.51) | (160.04) | (0.35) | (6.57) | (4.57) | (1.20) | (12.69) | - | (172.73) | - | 1,185.96 | - |
| 14 | 15 In-Vehicle Entertainment | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 15 | 17 Lighting | | (3.07) | 0.54 | 0.76 | (1.77) | (0.01) | (0.08) | (0.09) | (0.05) | (0.23) | - | (2.00) | - | - | - |
| 16 | 18 Electrical Distribution & Electrical Control | | 53.55 | 5.00 | (5.00) | 53.54 | 0.22 | 4.39 | 2.92 | 0.37 | 7.90 | - | 61.44 | - | 228.38 | - |
| 17 | 19 Electronic Features | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | SUBSYSTEM ROLL-UP | (1,569.63) | (138.54) | (263.38) | (1,973.58) | (3.49) | (35.27) | (40.43) | (22.87) | (102.06) | - | (2,074.72) | - | 7,251.31 | - |

As shown in **Table 3.1-4**, approximately 76% of the NIDMC increase is associated with material cost increases ($1,570). A breakdown of the primary material consumption, for both the baseline production stock and mass reduced vehicle, helps explain this fact.

For components and assemblies in each vehicle system, the primary material composition (e.g., steel, aluminum, magnesium, plastic, rubber, glass) were recorded for both the baseline vehicle and the mass-reduced version. These values are considered good directional estimates only since not all components were disassembled to a single material evaluation status; especially those components not evaluated in the detailed mass reduction and cost analysis step.

In **Figure 3.1-2** the summation of the system compositions equaling the vehicle totals are shown. The category referenced as miscellaneous "Misc." includes items where material composition by mass was not calculated (e.g. mass of items not included in analysis) and/or where material indentification was not relevant (e.g. fluids, paints, etc.). From the values presented in the pie-charts it is evident that the largest contributor to mass reduction came in the form of wrought aluminum substitution. The introduction of more magnesium and engineered plastics also played a role in vehicle mass reduction, though at a much smaller extent to wrought aluminum.



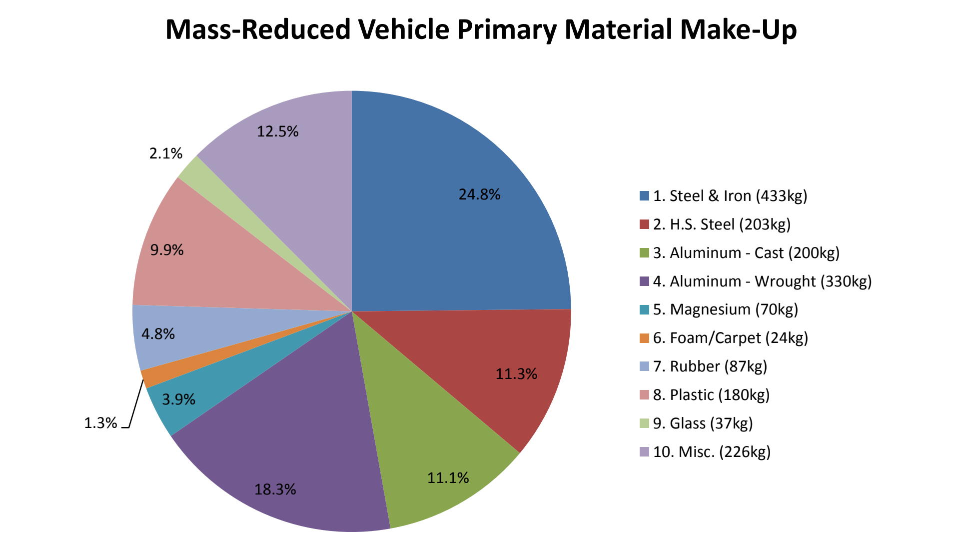




**Figure 3.1-3: General Material Make-up of Silverado Production Vehicle and Mass-Reduced Vehicle**

In **Table 3.1-1** and **Table 3.1-4** it is evident that the Body System Group -A- was the single largest contributor to vehicle mass-reduction (8.4%) making up nearly 37% of the overall mass reduction and accounting for nearly 58% of the cost increase. Further 89% of the mass reduction cost increase for Body System Group -A- was in material costs: the substitution of lighter more expensive wrought aluminum for heavier, less expensive coil steel. Aluminum costs three times more than steel per kilogram, but the cost premium is mitigated to some extent because the aluminum design weighs less: In this study, aluminum is 64% that of the steel design. **Section 4.18** covers additional details on the mass reduction and incremental costs associated with Body System Group -A-.

The process of producing aluminum from bauxite is a very energy intensive process. Alternatively, aluminum ingots can be produced from recycled aluminum requiring much less energy; energy conversion costs approaching that of steel. So neglecting economic basics from the pricing equation (i.e., law of supply and demand), one can see how a significant increase in aluminum production over the long-run could help drive the cost of aluminum down.

In 2013 approximately 69M vehicles were sold worldwide.[23] According to the European Aluminum Association, the primary aluminum consumption in 2013 worldwide was 50.2M[24] tonnes in 2013. If every car sold in the future used 100 kg of additional aluminum, the world market consumption would grow by 15% assuming no grow in other markets (200 kg = 30%, 300kg =45%, and 400 kg = 60%).

Though, growth in the aluminum market will certainly be challenged by growth in other advance light-weight material industries such as the steel, magnesium, carbon fiber and engineering plastics. The growth in alternative material markets will also have an impact on pricing in future years. In this study, no attempt was made to predict where material pricing would be in the 2020-2025 timeframe and how potentially lower cost materials would impact the overall results.

The cost curves shown below highlight the fact that not all mass reduction comes with an increase in direct manufacturing costs. In several examples material substitution, component substitution and/or component consolidation yielded a mass reduction result with a cost save. In **Figure 3.1-4**, approximately 6.3% vehicle mass-reduction was achieved at zero cost (without consideration to secondary mass-savings). When secondary mass-savings is considered, approximately 8% vehicle mass reduction was achieved at no cost. It should be pointed out that although the primary objective of the analysis was to derive ideas that created significant mass reduction opportunities, for some components the cost benefit of the change overshadowed the mass reduction benefit. The resultant is a build-up of a cost reduction credit which offset some of the more expensive mass reduction ideas. Approximately half of the mass reduction component/assembly/subsystem concepts selected generated a net cost savings of $259, contributing about 79 kg to the overall vehicle mass reduction. The remaining mass reduction concepts cost approximately $2,402 and reduced the vehicle mass an additional

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23. "Number of cars sold worldwide from 1990 to 2014 (in million units)," statista, accessed June 23, 2014. http://www.statista.com/statistics/200002/international-car-sales-since-1990/

24 "Primary Aluminum Consumption 2011-2103," European Aluminum Association, accessed June 23, 2014. http://www.alueurope.eu/consumption-primary-aluminium-consumption-in-world-regions/

397 kilograms. These numbers do not include secondary mass savings (i.e., mass reduction of 83.9 kg and cost savings of $68.74) nor the NVH countermeasure offsets (i.e., mass increase of 50 kg and cost increase of $150).

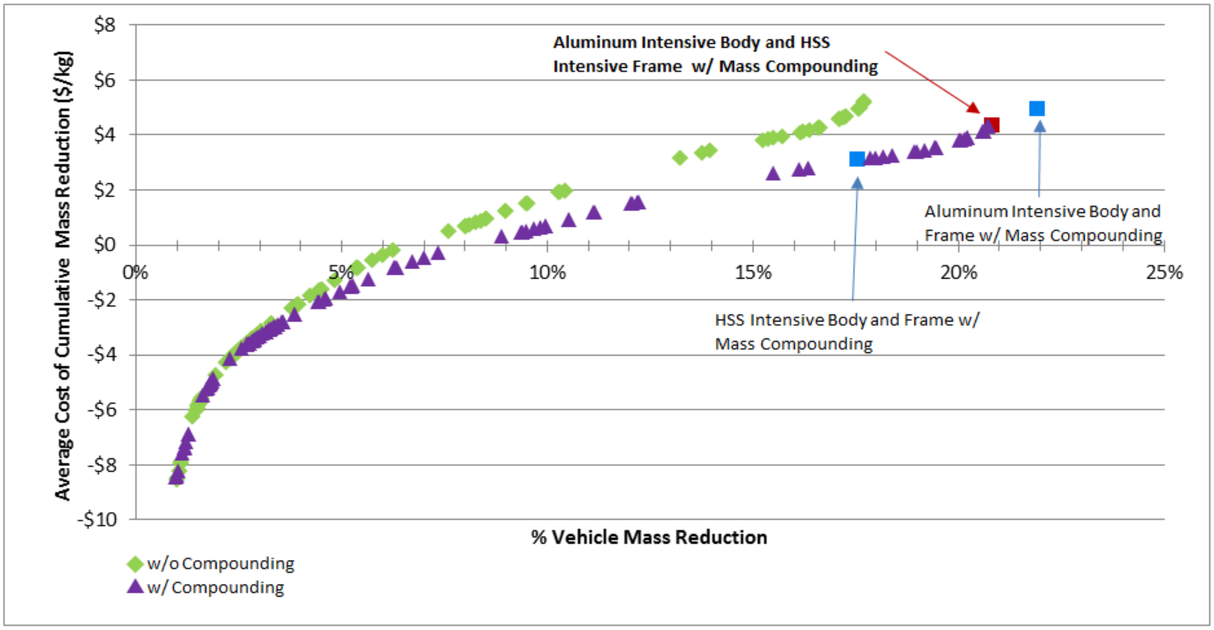


**Figure 3.1-4: Light-Duty Pickup Truck Cost Curves With and Without Mass Compounding**

**Figure 3.1-5** and **Figure 3.1-6** represent cost curves developed with components and assemblies from each of their respective evaluation groups. Both figures include component mass reduction data points with secondary mass-savings. Note in **Figure 3.1-6** there are no mass reduction data points which exist as cost reductions. Not having the ability to dilute the costs with cost savings or lower cost mass reduction ideas results in a much higher cost per kilogram for mass reduction.

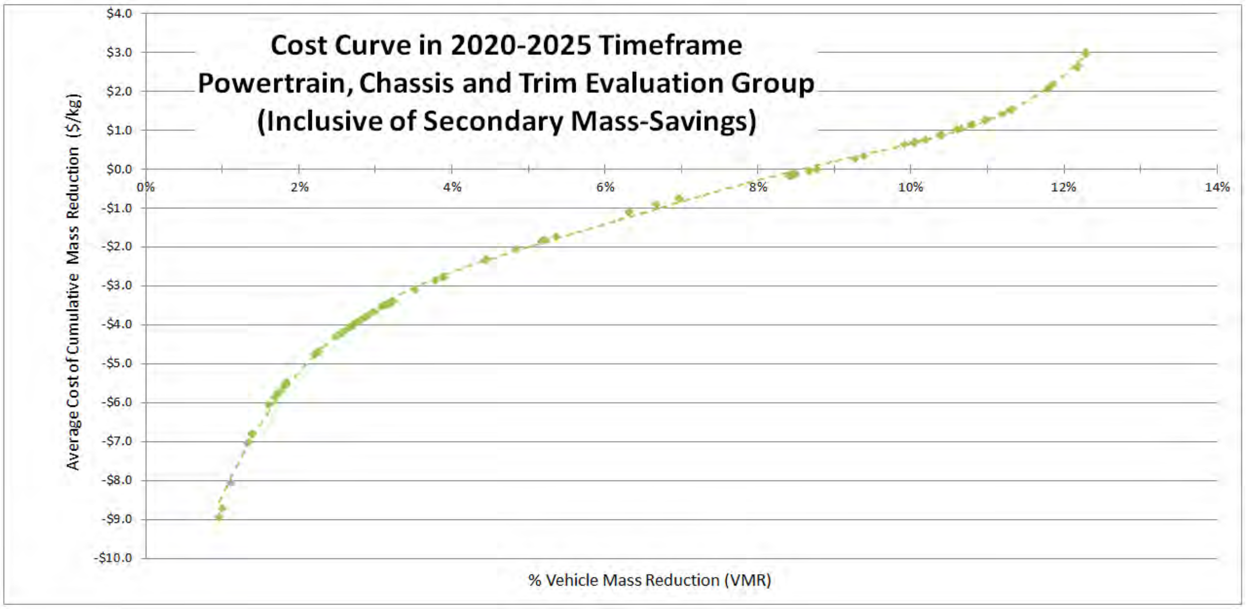


**Figure 3.1-5: Powertrain, Chassis and Trim Evaluation Group Cost Curve Inclusive of Secondary Mass-Savings**

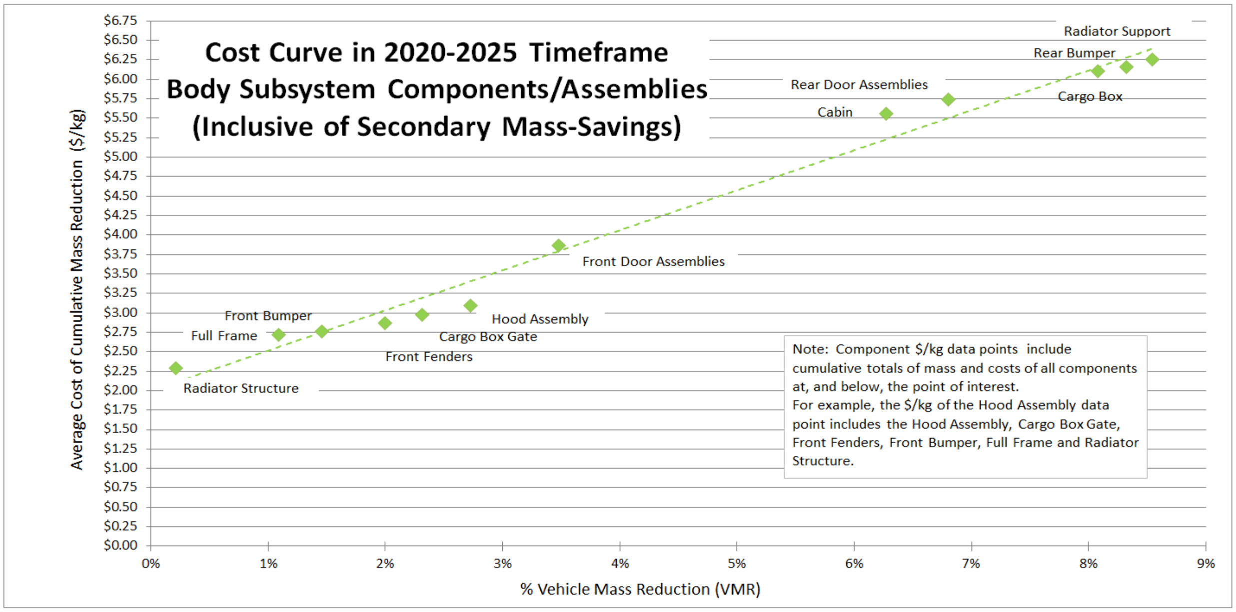


**Figure 3.1-6: Selective Body Subsystem Components/Assemblies Cost Curve Inclusive of Secondary Mass Savings**

## 3.2 Mass Reduction and Cost Analysis Results Overview – Vehicle Systems

**Sections 3.2.1** through **3.2.17** contain system summaries which highlight the major mass reduction ideas selected for each individual vehicle system.

For a more in-depth component review, a hyperlink to the parts location within the body of the relevant whitepaper in Section 4.1 is provided where both mass reduction and incremental cost impact are presented at the vehicle system level (e.g., Engine), subsystem level (e.g., Crank Drive) and sub-subsystem level (e.g., Piston). For each vehicle system evaluated, a major section (e.g., Section 4.1 Engine) has been devoted. Each vehicle system is broken down further into subsystems, each represented with its own subheadings (e.g., Section 4.1.1 Frame and Mounting, Section 4.1.2 Crankdrive, etc.).

Note that at the conclusion of each vehicle system section, references to the cited works can be found.

### 3.2.1 Engine System Overview

This following section identifies mass reduction alternatives and cost implications for the Engine System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). Not including secondary mass savings, the engine system mass was reduced by 23.8 kg (9.9%). This increased the cost by $114.63, or $4.82 per kg. Mass reduction for this system reduced vehicle curb weight by .97%. With secondary mass savings, the additional mass saving was 8.0 kg for a total system mass reduction of 31.8 kg (1.3% curb weight reduction). The increase in costs was reduced by $21.81 due to secondary mass savings resulting in a total system cost of -$92.83 or -$2.92 per kg.

**Table 3.2-1** provides a summary of mass reduction and cost impact for select sub-subsystems evaluated. Only sub-subsystems with significant mass savings were included in the table, and account for over 80% of the total mass savings found on the engine. The table does not include secondary mass savings and associated cost benefits. The additional benefits of secondary mass savings are included in the detail engine system review (Section 4.1).

**Table 3.2-1: Engine System Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 01 | 00 | 00 | **Engine System** | | | | | | | | |
| 01 | 02 | 00 | Engine Frames, Mounting, and Brackets Subsystem | 1.10 | 0.348 | 1.45 | -$0.01 | $0.58 | $0.57 | $0.39 | 0.1% |
| 01 | 03 | 00 | Crank Drive Subsystem | 2.38 | 2.11 | 4.49 | $2.95 | $4.10 | $7.05 | $1.57 | 0.2% |
| 01 | 04 | 00 | Counter Balance Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 05 | 00 | Cylinder Block Subsystem | 3.30 | 3.07 | 6.36 | $0.80 | $9.35 | $10.15 | $1.60 | 0.3% |
| 01 | 06 | 00 | Cylinder Head Subsystem | 1.16 | 1.21 | 2.37 | $6.06 | $3.69 | $9.75 | $4.11 | 0.1% |
| 01 | 07 | 00 | Valvetrain Subsystem | 0.192 | 0.126 | 0.318 | $0.05 | $0.45 | $0.50 | $1.57 | 0.0% |
| 01 | 08 | 00 | Timing Drive Subsystem | 0.415 | 0.00 | 0.415 | -$2.44 | $0.00 | -$2.44 | -$5.88 | 0.0% |
| 01 | 09 | 00 | Accessory Drive Subsystem | 1.73 | 0.325 | 2.06 | $0.73 | $0.00 | $0.73 | $0.35 | 0.1% |
| 01 | 10 | 00 | Air Intake Subsystem | 0.941 | 0.00 | 0.941 | -$0.54 | $0.00 | -$0.54 | -$0.58 | 0.0% |
| 01 | 11 | 00 | Fuel Induction Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 12 | 00 | Exhaust Subsystem | 3.15 | 0.28 | 3.43 | -$20.00 | $0.97 | -$19.03 | -$5.56 | 0.1% |
| 01 | 13 | 00 | Lubrication Subsystem | 3.01 | 0.112 | 3.12 | -$11.24 | $0.55 | -$10.69 | -$3.42 | 0.1% |
| 01 | 14 | 00 | Cooling Subsystem | 3.31 | 0.457 | 3.77 | -$92.06 | $2.11 | -$89.95 | -$23.85 | 0.2% |
| 01 | 15 | 00 | Induction Air Charging Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 16 | 00 | Exhaust Gas Re-circulation Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 17 | 00 | Breather Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 60 | 00 | Engine Management, Engine Electronic, Electrical Subsystem | 0.886 | 0.00 | 0.886 | $1.97 | $0.00 | $1.97 | $2.23 | 0.0% |
| 01 | 70 | 00 | Accessory Subsystems (Start Motor, Generator, etc.) | 2.23 | 0.00 | 2.23 | -$0.89 | $0.00 | -$0.89 | -$0.40 | 0.1% |
| | | | | **23.8** (Decrease) | **8.0** (Decrease) | **31.8** (Decrease) | **-$114.63** (Increase) | **$21.81** (Decrease) | **-$92.83** (Increase) | **-$2.92** (Increase) | **1.30%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

Mass savings opportunities were identified for the following components: crankshaft, connecting rod, cylinder block, cylinder head covers, camshafts, pulleys, exhaust manifolds, oil pans, water pump, radiator, and accessory drive bracket.

**Crankshaft**: The crankshaft mass was reduced by changing the cast crankshaft to a hollow cast design. The main bearing journals were cast with a core to remove excess material. Mass was reduced by 4.3% from 24.0 kg to 23.0 kg.

Production applications include the BMW 4.4L V8 and the Nissan 4.5L V8.

**Connecting Rod**: Connecting rod mass reduction was achieved by changing the primary forming operation from powder forged to billet forged. The connecting rod mass was reduced by 19.8% from 5.41 kg to 4.34 kg.

FEV validated this change by creating CAD models for both connecting rods and performing fatigue analysis. Mahle manufactures connecting rods using this technology.

**Cylinder Block**: Cylinder block mass was reduced by replacing cast iron bore liners with plasma liner technology. Mass was reduced by 6.2% from 47.1 kg to 44.2 kg.

Production vehicles utilizing this technology include Nissan GT-R, 2011 Shelby Mustang GT500, and Volkswagen Lupo.

**Cylinder Head Covers**: Aluminum valve covers were replaced by plastic. Mass was reduced by 44.0% from 2.64 kg to 1.48 kg.

Production examples include Chrysler's 4.7L V8 and the Ford Duratec® 2.0L.

**Pulleys**: The idler, crank, and AC compressor pulleys were all found to have lightweighting opportunities. The steel idler pulley was replaced with a plastic design, which reduced mass by 58.0% from 0.455 kg to 0.191 kg. Plastic idler pulleys are commonplace and have proven durability.

The AC compressor pulley was changed from steel to plastic, which reduced mass by 59.8% from 0.695 kg to 0.279 kg. The Volkswagen Polo is a production example containing a plastic AC compressor pulley.

**Exhaust Manifold**: Cast iron exhaust manifolds were replaced by fabricated sheet steel manifolds. Mass was reduced by 26.0% from 12.2 kg to 9.0 kg.

Production examples include the Toyota Avensis 2.0-R4 4V. Fabricated manifolds with integrated catalyst are common for quick light off.

**Oil Pan**: Mass reduction of the oil pan was achieved by replacing aluminum with magnesium. Mass was reduced by 25% from 5.27 kg to 3.96 kg. The Nissan GT-R oil pan is constructed from magnesium.

Steel baffle plates were used to control oil flow within the oil pan region. These stamped steel plates were changed to plastic. Mass was reduced by 70.6% from 1.65 kg to 0.49 kg. The Ford Mustang utilizes plastic for this component.

**Water Pump**: The conventional mechanical water pump was replaced with an electric water pump. Mass was reduced by 51.9% from 4.68 kg to 2.43 kg.

Electric water pumps are found on vehicles such as the BMW 328, 528, and X3/5.

**Radiator**: The radiator found on Silverado is designed for a range of applications. A radiator designed specifically for the 5.3L Silverado could be smaller reducing component and fluid mass. Mass was reduced by 4.0% from 6.785 kg to 6.520 kg. MuCell® applied to the fan shroud and fan blades, which yielded an additional mass savings of 0.32 kg.

**Accessory Drive Bracket**: The accessory drive bracket provides mounting for both the alternator and power steering pump. This aluminum component was replaced with a magnesium version and the power steering provision eliminated as this feature is no longer needed with electric power steering. Mass was reduced by 50.5% from 3.69 kg to 1.83 kg.

An example of a magnesium bracket can be found on the Nissan 350Z.

### 3.2.2 Transmission System Overview

This following section identifies mass reduction alternatives and cost implications for the Transmission System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). Not including secondary mass savings, the transmission system mass was reduced by 34.19 kg (23.53%). This increased the cost by $128.20, or $3.75 per kg. Mass reduction for this system reduced vehicle curb weight by 1.43%. With secondary mass savings, the additional mass savings was 5.17 kg for a total system mass reduction of 39.4 kg (1.60% curb weight reduction). The increase in cost was reduced by $31.64 due to secondary mass savings resulting in a total system cost increase of $96.57 or $2.45 per kg.

**Table 3.2-2** provides a summary of mass reduction and cost impact for select sub-subsystems evaluated. The table does not include secondary mass savings and associated cost benefits. The additional benefits of secondary mass savings are included in the detailed Transmission Section review (Section 4.2).

**Table 3.2-2: Transmission System Mass and Cost Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| **02** | **00** | **00** | **Transmission System** | | | | | | | | |
| 02 | 01 | 00 | External Components | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 02 | 02 | 00 | Case Subsystem | 10.7 | 1.27 | 11.9 | -$30.60 | $5.09 | -$25.50 | -$2.14 | 0.49% |
| 02 | 03 | 00 | Gear Train Subsystem | 2.05 | 0.650 | 2.70 | $24.18 | $2.41 | $26.59 | $9.84 | 0.11% |
| 02 | 04 | 00 | Internal Clutch Subsystem | 4.23 | 1.18 | 5.41 | -$39.94 | $8.53 | -$31.41 | -$5.80 | 0.22% |
| 02 | 05 | 00 | Launch Clutch Subsystem | 8.62 | 1.13 | 9.7 | -$21.73 | $2.42 | -$19.32 | -$1.98 | 0.40% |
| 02 | 06 | 00 | Oil Pump and Filter Subsystem | 2.42 | 0.044 | 2.46 | -$11.52 | $1.79 | -$9.73 | -$3.95 | 0.10% |
| 02 | 07 | 00 | Mechanical Controls Subsystem | 0.872 | 0.146 | 1.02 | -$5.03 | $1.68 | -$3.35 | -$3.29 | 0.04% |
| 02 | 08 | 00 | Electrical Controls Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 02 | 09 | 00 | Parking Mechanism Subsystem | 0.060 | 0.00 | 0.064 | $5.24 | $0.31 | $5.55 | $86.61 | 0.00% |
| 02 | 10 | 00 | Misc. Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 02 | 11 | 00 | Electric Motor & Controls Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 02 | 12 | 00 | Transfer Case Subsystem | 5.27 | 0.743 | 6.01 | -$48.81 | $9.41 | -$39.40 | -$6.55 | 0.25% |
| 02 | 20 | 00 | Driver Operated External Controls Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| | | | | **34.2** (Decrease) | **5.17** (Decrease) | **39.4** (Decrease) | **-$128.20** (Increase) | **$31.64** (Decrease) | **-$96.57** (Increase) | **-$2.45** (Increase) | **1.60%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the Transmission subsystem are the torque converter, case subsystems, drive gears and shafts, and the oil pump.

**Case Subsystem**: The mass reduction idea for the Case Subsystem is to change the component material from aluminum to magnesium. The individual baseline component mass was 30.7 kg and the redesign mass was 20.1 kg, resulting in an overall mass savings of 10.6 kg (34.7%) compared to the aluminum units.

One production example of a magnesium transmission case is the Mercedes-Benz 7G-TRONIC. General Motors also has approximately 1 million GMT800 full-size trucks and sport utility vehicles (SUV) that are produced annually that have a magnesium transfer case in their design.

**Gear Train Subsystem**: The mass reduction idea for the sun, ring, and planet gears was to change the base component material from standard gear steel to high-strength options. The individual baseline component mass was 10.9 kg while the redesign mass was 9.28 kg, which resulted in an overall mass savings of 1.64 kg (15%) compared to the standard steel components.

**Internal Clutch Subsystem**: The mass reduction idea for the clutch and brake hubs was to change the base component material from 4140 and powder metal to C61 and MMC. The individual baseline component mass was 20.74 kg, with the redesign mass 16.90 kg, resulting in an overall mass savings of 3.84 kg (18.5%) for these components.

**Torque Converter**: The mass reduction idea for the torque converter was to use a full aluminum torque converter assembly for this application instead of the industry standard steel unit. Aluminum torque converters are presently used in off-road, racing, heavy industrial equipment, and some automotive applications. A cast design of an aluminum turbine, impeller, and housing will reduce the assembly steps in process and make for a simpler assembly.

The individual baseline component mass was 19.3 kg, and the redesign mass was 10.7 kg for an overall mass savings of 8.62 kg (44.6%) for both arms compared to the steel units.

**Oil Pump**: The mass reduction idea for the oil pump was to change the base component material from cast iron to aluminum. The individual baseline component mass was 4.71 kg, and the redesign mass 3.27 kg, which resulted in a mass savings of 1.44 kg (30.6%) compared to the cast iron units.

**Transfer Case Subsystem**: The major mass reduction ideas for the transfer case were the gear materials and drive shaft configuration. The gears were standard gear steels and the shafts solid steel bars. These were converted to high-strength gear steels and hollow drive shafts, which are currently used by OEMs in their systems. The change to the base component materials mass was 12.75 kg and the redesign mass was 10.50 kg, resulting in an overall mass savings of 2.25 kg (17.3%) for these components.

#### 3.2.3 Body System Group -B- (Interior) Overview

This report identifies mass reduction alternatives and cost implications for the Body Group -B- system with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). **Table 3.2-3** shows a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This project recorded a system mass reduction of 34.0 kg (13.8%) at a cost increase of -$127.23, or -$3.74/ kg. The contribution of the Body Group -B- system to the overall vehicle mass reduction is 1.39%. There are no compounding mass reductions for this system.

**Table 3.2-3: Body System Group -B- Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Net Value of Mass Reduction** | | | | | | | |
| 03 | 00 | 00 | Body Group B | | | | | | | | |
| 03 | 05 | 00 | Interior Trim and Ornamentation Subsystem | 2.06 | 0.00 | 2.06 | $6.84 | $0.00 | $6.84 | $3.32 | 0.08% |
| 03 | 06 | 00 | Sound and Heat Control Subsystem (Body) | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 03 | 07 | 00 | Sealing Subsystem | 4.72 | 0.00 | 4.72 | $32.23 | $0.00 | $32.23 | $6.84 | 0.19% |
| 03 | 10 | 00 | Seating Subsystem | 19.2 | 0.00 | 19.2 | -$127.89 | $0.00 | -$127.89 | -$6.68 | 0.78% |
| 03 | 12 | 00 | Instrument Panel and Console Subsystem | 6.82 | 0.00 | 6.82 | -$35.29 | $0.00 | -$35.29 | -$5.17 | 0.28% |
| 03 | 20 | 00 | Occupant Restraining Device Subsystem | 1.26 | 0.00 | 1.26 | -$3.12 | $0.00 | -$3.12 | -$2.47 | 0.05% |
| | | | | **34.0** (Decrease) | **0.00** | **34.0** (Decrease) | **-$127.23** (Increase) | **$0.00** | **-$127.23** (Increase) | **-$3.74** (Increase) | **1.39%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the Body Group -B- system are the front seats back and bottom frames, 60/40 seat back and bottom frames and the cross car beam.

**Front Driver/Passenger Back and Bottom Seat Frames**: The mass reduction idea for the front driver and passenger back and bottom seat frames was to change the base steel-welded seat construction to continuous fiber reinforced plastic tape and laminate construction. The baseline component mass was 11.59 kg, while the redesign mass was 5.80 kg, resulting in an overall mass savings of 5.79 kg (50%).

The continuous fiber reinforced plastic tape and laminate construction was developed by BASF®. The laminate has been put into production on the Opal Astra vehicles front seat bottom frame. BASF® has also passed OEM test requirements on this technology for the front seat back frames.

**Rear 60/40% Seat Frames**: The mass reduction idea for the 60/40 seat back and bottom frames was to change the base welded steel construction to die-cast magnesium by Meridian®. The individual baseline component mass was 16.20 kg, with the redesign mass at 7.87 kg, resulting in an overall mass savings of 8.33 kg (51%).

Some of Meridian's products include the Ford F150 bolster, the Dodge Viper front of dash, the Lincoln MKT lift gate, GM instrument panels, as well as seat frames for Ford's Explorer and Flex, the Mercury Mountaineer, and the Chevrolet Corvette.

**Cross Car Beam**: The mass reduction idea for the cross car beam was to change the base-welded steel construction to die-cast magnesium by Meridian. The individual baseline component mass was 11.92 kg, and the redesign mass was 6.48 kg, resulting in an overall mass savings of 5.44 kg (48%).

### 3.2.4 Body System -C- (Exterior) Overview

This report identifies mass reduction alternatives and cost implications for the **Body System -C-** (Exterior)System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). **Table 3.2-4** is a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This project recorded a system mass reduction of 2.14 kg (5.28%) at a cost decrease of $2.73, or $1.28 per kg. The contribution of the Body Group -C- system to the overall vehicle mass reduction was 0.09%. There are no compounding mass reductions for this system.

**Table 3.2-4: Body System Group -C- Mass Reduction Summary**

| | | | | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 03 | 00 | 00 | Body Group C | | | | | | | | |
| 09 | 01 | 00 | Exterior Trim and Ornamentation Subsystem | 0.989 | 0.00 | 0.989 | $1.05 | $0.00 | $1.05 | $1.06 | 0.04% |
| 09 | 01 | 00 | Rear View Mirrors Subsystem | 0.373 | 0.00 | 0.373 | $0.94 | $0.00 | $0.94 | $2.51 | 0.02% |
| 09 | 01 | 00 | Front End Modules | 0.575 | 0.00 | 0.575 | $0.50 | $0.00 | $0.50 | $0.87 | 0.02% |
| 09 | 01 | 00 | Rear End Modules | 0.200 | 0.00 | 0.200 | $0.24 | $0.00 | $0.24 | $1.20 | 0.01% |
| | | | | **2.14** (Decrease) | **0.00** | **2.14** (Decrease) | **$2.73** (Decrease) | **$0.00** | **$2.73** (Decrease) | **$1.28** (Decrease) | **0.09%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The minimal mass reductions of this system were to use PolyOne® injection molding process to reduce the mass of the plastic components.

### 3.2.5 Body System Group -D- Overview

This report identifies mass reduction alternatives and cost implications for the Body System Group -D- System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). **Table 3.2-5** is a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This project recorded a system mass reduction of 4.50 kg (8.85%) at a cost decrease of $2.30, or $0.51 per kg. The contribution of the Body Group -D- system to the overall vehicle mass reduction was 0.18%. There are no compounding mass reductions for this system.

**Table 3.2-5: Body Group -D- Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 03 | 00 | 00 | **Body System (Group D) Glazing** | | | | | | | | |
| 03 | 11 | 00 | Glass (Glazing), Frame and Mechanism Subsystem | 4.429 | 0.00 | 4.43 | $2.23 | $0.00 | $2.23 | $0.50 | 0.18% |
| 03 | 14 | 00 | Handles, Locks, Latches and Mechanisms Subsystem | 0.000 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 03 | 16 | 00 | Wipers and Washers Subsystem | 0.074 | 0.00 | 0.07 | $0.06 | $0.00 | $0.06 | $0.84 | 0.00% |
| | | | | **4.50** (Decrease) | **0.00** | **4.50** (Decrease) | **$2.30** (Decrease) | **$0.00** | **$2.30** (Decrease) | **$0.51** (Decrease) | **0.18%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The minimal mass reduction for this system was in the Glass (Glazing) subsystem. The reduction made was to thin the glass in the windshield, back window, and rear side door glass.

### 3.2.6 Suspension System Overview

This following section identifies mass reduction alternatives and cost implications for the Suspension System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). Not including secondary mass savings, the suspension system mass was reduced by 83.1 kg (27.6%). This increased the cost by $260.84, or $3.14 per kg. Mass reduction for this system reduced vehicle curb weight by 3.39%. With secondary mass savings, the additional mass savings was 22.4 kg for a total system mass reduction of 105.4 kg (4.30% curb weight reduction). The increase in cost was reduced by $105.94 due to secondary mass savings resulting in a total system cost of $154.90 or $1.47 per kg.

**Table 3.2-6** provides a summary of mass reduction and cost impact for select sub-subsystems evaluated. The table does not include secondary mass savings and associated cost benefits. The additional benefits of secondary mass savings are included in the detailed Suspension System review (Section 4.6).

**Table 3.2-6: Suspension System Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 04 | 00 | 00 | Suspension System | | | | | | | | |
| 04 | 01 | 00 | Front Suspension Subsystem | 21.3 | 2.44 | 23.8 | -$23.71 | $10.07 | -$13.64 | -$0.57 | 1.0% |
| 04 | 02 | 00 | Rear Suspension Subsystem | 35.7 | 2.66 | 38.4 | -$113.47 | $29.42 | -$84.06 | -$2.19 | 1.6% |
| 04 | 03 | 00 | Shock Absorber Subsystem | 6.44 | 0.694 | 7.14 | -$3.77 | $2.88 | -$0.89 | -$0.12 | 0.3% |
| 04 | 04 | 00 | Wheels And Tires Subsystem | 19.6 | 16.6 | 36.1 | -$119.89 | $63.57 | -$56.32 | -$1.56 | 1.5% |
| | | | | **83.1** (Decrease) | **22.4** (Decrease) | **105.4** (Decrease) | **-$260.84** (Increase) | **$105.94** (Decrease) | **-$154.90** (Increase) | **-$1.47** (Increase) | **4.30%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the Front Suspension Subsystem are the lower control arms, upper control arms, steering knuckles, and the stabilizer bar.

**Lower Control Arm**: The mass reduction idea for the lower control arms was to change the component material from cast iron to aluminum. The individual baseline component mass was 9.55 kg and the redesign mass was 5.10 kg, resulting in an overall mass savings of 8.37 kg (46.6%) compared to the steel units.

GM offered in 2009 two XFE (eXtra Fuel Economy) models for the Chevrolet Silverado and the GMC Sierra, which included among other fuel saving ideas, aluminum lower control arms. The aluminum control arms were eventually switched back to cast iron due to cost-reduction efforts. GM announced that the 2014 Silverado will come equipped with aluminum control arms and aluminum knuckles.

**Upper Control Arm**: The mass reduction ideas for the upper control arms were to normalize the control arm dimensions described as follows based on the 2012 Dodge Durango, and change the component material from forged steel to cast magnesium.

The normalizing process compares the gross vehicle weight (GVW) of the Durango to the GVW of the Silverado and adjusts the mass of the Silverado control arm, up or down, based on the ratios of the two vehicles' GVW and the component mass of the Durango control arm. As a result of this normalization process the baseline mass of the Silverado control arm was reduced by 1.72 kg.

The individual baseline component mass was 2.28 kg and the redesign mass was 0.759 kg, resulting in an overall mass savings of 3.04 kg (66.7%) for both arms compared to the steel units.

**Steering Knuckle**: The mass reduction idea for the steering knuckles is to change the base component material from steel to aluminum. The individual baseline component mass was 7.67 kg with the redesign mass 3.73 kg, resulting in an overall mass savings of 7.88 kg (51.4%) for both knuckles compared to steel.

**Leaf Spring Assembly**: The major component contributing to the mass reduction within the Rear Suspension subsystem was the rear leaf spring assembly. The mass reduction idea for the rear leaf spring assemblies was to change the base component material from steel to glass fiber reinforced plastic. The individual baseline component mass was 26.2 kg and the redesign mass 10.5 kg, resulting in an overall mass savings of 31.4 kg (60%) for both leaf spring assemblies compared to the steel units.

LITEFLEX® LLC, a manufacturer of OEM composite leaf springs, has supplied composite leaf springs since 1998 to support production requirements on the Sprinter commercial vehicles, namely the NCV3 Sprinter. Other vehicles using Liteflex composite leafs springs are the Chevrolet Corvette and the Land Rover. Liteflex also produces composite leaf springs for heavy-duty truck applications for Kenworth, Peterbilt, Freightliner, and International.

Liteflex states "Suspension designers realized a 55% reduction in weight when replacing two steel leaf springs with Liteflex lightweight composite springs for ¾ ton 4x4 pickup. The original, all-steel design tipped the scales at 69 pounds while the hybrid steel-and-composite version weighed in at just 31 pounds."

The major component contributing to the mass reduction within the Shock Absorber subsystem was the Front Strut Coil Spring.

**Front Strut Coil Spring**: The mass reduction idea for the front strut coil springs is to change the base component material from steel to the Mubea HSLA steel coil. The individual baseline component mass was 5.35 kg, while the redesign mass was 2.73 kg, resulting in an overall mass savings of 5.24 kg (49.0%) for both springs compared to the steel units.

The major components contributing to the mass reduction within the Wheels and Tires subsystem are the road wheels, road tires, spare wheel, and spare tire.

**Road Wheels**: The mass reduction idea for the road wheels is to change the base component material from aluminum to ultra-light weight forged aluminum. The total baseline component mass was 48.5 kg and the total redesign mass 42.4 kg, resulting in an overall mass savings of 6.1 kg (12.6%) for all four wheels compared to the steel units.

**Road Tires**: The mass reduction idea for the road tires was to normalize the base tires to the 2007 Ford F-150 road tires. The total baseline component mass was 69.5 kg, and the redesign mass 63.9 kg, resulting in an overall mass savings of 5.60 kg (8%) for all four tires compared to the Silverado road tires.

**Spare Wheel**: The mass reduction idea for the spare wheel was to change the base component material from stamped steel to cast aluminum. The baseline component mass was 15.5 kg and the redesign mass 9.24 kg, resulting in an overall mass savings of 6.26 kg (40.4%) compared to the steel unit.

**Spare Tire**: The mass reduction idea for the spare tire was to replace the base component with the 2006 Dodge Ram spare tire. The baseline component mass was 17.0 kg and the redesign mass was 14.9 kg, an overall mass savings of 2.1 kg (12.4%) compared to the Silverado spare tire.

### 3.2.7 Driveline System Overview

This report identifies mass reduction alternatives and cost implications for the Driveline System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado).

The Driveline Subsystem contributed a system mass reduction of 20.5 kg. This mass reduction provided a vehicle cost save of $38.01, which equates to $1.86 per kg. The overall vehicle mass reduction contribution is 0.83%. **Table 3.2-7** is a summary of the calculated mass reduction and cost impact for each vehicle subsystem evaluated. There are no compounding mass reductions for this system.

**Table 3.2-7: Driveline System Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction | | | | | | | |
| 05 | 00 | 00 | **Driveline System** | | | | | | | | |
| 05 | 01 | 00 | Driveshaft Subsystem | 2.10 | 0.00 | 2.10 | $3.38 | $0.00 | $3.38 | $1.61 | 0.09% |
| 05 | 02 | 00 | Rear Drive Housed Axle Subsystem | 10.5 | 0.00 | 10.5 | $25.78 | $0.00 | $25.78 | $2.46 | 0.43% |
| 05 | 03 | 00 | Front Drive Housed Axle Subsystem | 6.49 | 0.00 | 6.49 | $6.27 | $0.00 | $6.27 | $0.97 | 0.26% |
| 05 | 04 | 00 | Front Drive Half-Shaft Subsystem | 1.36 | 0.00 | 1.36 | $2.58 | $0.00 | $2.58 | $1.90 | 0.06% |
| 05 | 05 | 00 | Rear Drive Half Shaft Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 05 | 07 | 00 | 4WD Driveline Control System | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| | | | | **20.4** (Decrease) | **0.00** | **20.4** (Decrease) | **$38.01** (Decrease) | **$0.00** | **$38.01** (Decrease) | **$1.86** (Decrease) | **0.83%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The Driveline System was coupled to the engine/transmission assembly and is designed to deliver the energy generated by the engine, passed through the transmission to the wheels.

In four-wheel drive (4WD) mode, the transmission provides energy to the transfer case. The output shaft of the transfer case and the front axle differential are all connected with the same type of universal/yoke/driveshaft assembly as the rear axle. The front differential operates in the same manner as the rear, when engaged.

The Driveline System is made up of six subsystems. The Silverado analysis and mass reduction efforts focused on the top four subsystems. The last two subsystems have little mass in the total system mass of this vehicle. This lack of mass and content did not provide any opportunities for mass reduction.

**Driveshaft Subsystem**: This subsystem carries a mass of 14.3 kg. Mass reduction in this system was achieved by changing the front driveshaft material from steel to aluminum. This change provided a sub system mass reduction of 2.10 kg (14.6%), with a cost saving of $3.38, at $1.61 per kg.

This vehicle was equipped with two driveshafts: one rear and one forward. The rear driveshaft was manufactured of aluminum, which was the only mass reduction idea generated. The front driveshaft was manufactured of steel. The use of aluminum requires more aluminum to maintain the torsional strength, which may only be accomplished by increasing the diameter. The need to maintain the packaging envelope was the main reason aluminum was not selected for the front driveshaft, although providing more packaging space might enable the material's use in the future.

**Rear Drive Housed Axle Subsystem, Beam Rear Axle Assembly:** This subsystem carries the bulk of the mass for the Driveline System, 89.07 kg. The mass reduction ideas provided a subsystem mass reduction of 10.5 kg (11.8%), with a cost saving of $25.78, equating to $2.46 per kg.

Approximately two-thirds of this subsystem mass is contained in the rear beam axle assembly sub-subsystem (66.6 kg).

Using the proprietary VARI-LITE® tube process of U.S. Manufacturing from Warren, Michigan, a mass saving of approximately 20% per axle housing was attained. This is an extrusion process that strategically thins the axle tubing without sacrificing any structural integrity. This process is in production today and is used by the Ford Motor Company on the F-Series pickup truck axle housing.

The same technology can be applied to the axle shaft, yielding an approximate 25% mass savings per axle assembly.

**Rear Drive Housed Axle Subsystem, Rear Drive Unit:** The Schaeffler Group from Troy, Michigan, has developed a new design for the differential gearing configuration that uses lower density materials, innovative shapes, and assembly creations. The new design is currently undergoing testing for rear-wheel drive (RWD) vehicle applications.

The concept and design was originally developed for front-wheel drive (FWD) applications. As the FWD market grew and vehicles became smaller, there was an opportunity to create a FWD differential assembly. One of the design criteria was to make the new differential more compact in design to accommodate the smaller packaging requirements vehicle OEMs were designing. This idea is expected to remove a minimum of 2.5 kg of mass from the vehicle.

**Front-Drive Housed Axle Subsystem:** This subsystem is able to accommodate the same differential modification as the rear drive unit. The design from Schaeffler is a little bit lighter due to the application, but very similar.

The Front Drive Housed Axle Subsystem can also remove some additional mass through utilization of the U.S. Manufacturing VARI-LITE tube process for the manufacturing process in making the front differential output shaft.

The lighter differential assembly allowed a slight reduction in the strength of the brackets by changing the front differential mounting brackets material from forged steel to forged aluminum. Forged aluminum was selected as the new material.

**Front Drive Half-Shaft Subsystem:** The Front Drive Half Shaft Subsystem mass reduction was reduced by again employing the VARI-LITE tube process. This change created a mass reduction of just over 1.00 kg.

This process change is already in production for rear axle shafts and FWD axle shafts and is no different than the rear axle shaft application.

### 3.2.8 Brake System Overview

This following section identifies mass reduction alternatives and cost implications for the Brake System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). Not including secondary mass savings, the Brake system mass was reduced by 43.9 kg (43.4%). This increased the cost by $171.89, or $3.92 per kg. Mass reduction for this system reduced vehicle curb weight by 1.79%. With secondary mass savings, the additional mass savings was 2.58 kg for a total system mass reduction of 46.5 kg (1.87% curb weight reduction). The increase in costs was reduced by $18.95 due to secondary mass savings resulting in a total system cost of $152.94 or $3.29 per kg.

**Table 3.2-8** provides a summary of mass reduction and cost impact for select sub-subsystems evaluated. The table does not include secondary mass savings and associated cost benefits. The additional benefits of secondary mass savings are included in the detailed Brake System review (Section 4.8).

**Table 3.2-8: Brake System Mass Production Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 06 | 00 | 00 | **Brake System** | | | | | | | | |
| 06 | 03 | 00 | Front Rotor/Drum and Shield Subsystem | 22.0 | 1.06 | 23.1 | -$56.20 | $10.84 | -$45.35 | -$1.97 | 0.94% |
| 06 | 04 | 00 | Rear Rotor/Drum and Shield Subsystem | 16.3 | 0.89 | 17.2 | -$71.02 | $8.11 | -$62.91 | -$3.66 | 0.70% |
| 06 | 05 | 00 | Parking Brake and Actuation Subsystem | 1.45 | 0.00 | 1.45 | -$15.56 | $0.00 | -$15.56 | -$10.72 | 0.06% |
| 06 | 06 | 00 | Brake Actuation Subsystem | 2.53 | 0.00 | 2.53 | -$0.46 | $0.00 | -$0.46 | -$0.18 | 0.10% |
| 06 | 07 | 00 | Power Brake Subsystem (for Hydraulic) | 1.58 | 0.00 | 1.58 | -$24.64 | $0.00 | -$24.64 | -$15.57 | 0.06% |
| | | | | **43.9** (Decrease) | **1.96** (Decrease) | **45.8** (Decrease) | **-$167.87** (Increase) | **$18.95** (Decrease) | **-$148.92** (Increase) | **-$3.25** (Increase) | **1.87%** |

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the Front Rotor/Drum and Shield subsystem are the front rotor, caliper housing, and caliper mounting bracket.

**Front Rotor**: The mass reduction idea for the Front Rotor involved making several different changes to the baseline design. The changes include normalizing to the 2006 Dodge Ram two-piece rotor design, changing disc material from steel to an aluminum metal matrix material, change cooling vanes from a straight to directional configuration, and strategically adding cross-drilled holes to the rotor disc. The individual baseline component mass was 11.66 kg while the redesign mass was 5.60 kg, resulting in an overall mass savings of 12.11 kg (48.0%) compared to the steel units.

Each of these individual rotor ideas is not unique; however, it is unique to see all of them incorporated into a single design. This redesigned rotor incorporates all the latest rotor lightweighting ideas into a single unit that captures all the potential weight saving opportunities.

**Caliper Housing**: The mass reduction ideas for the caliper housing were to normalize to the 2002 Chevrolet Avalanche 1500 and then change the component material from cast iron to cast magnesium. The individual baseline component mass was 4.80 kg and the redesign mass 1.60 kg, resulting in an overall mass savings of 6.41 kg (66.7%) compared to the steel units.

For the caliper housing, as well as several other brake components, magnesium was the redesign material of choice. While this is not popular within the United States automotive industry, it is much more common with the European OEMs.

Magnesium has long been used in commercial and specialty automotive vehicles. Racing cars have used magnesium parts since the 1920s. Volkswagen used approximately 20.0 kg of magnesium in its 1936 Beetle powertrain system.

Over the past 10 years, there has been significant growth in the high-pressure die-casting sector as OEMs have been searching for light-weighting opportunities. With advances in the creation of magnesium alloys, there are many applications for the automotive industry particularly within the brake and suspension systems.

In Europe, Volkswagen, Chrysler, BMW, Ford, and Jaguar are using magnesium as a structural lightweight material. Presently, around 14.0 kg of magnesium is used in the Volkswagen Passat and the Audi A4 and A6 for transmission castings. Other applications include instrument panels, intake manifolds, cylinder head covers, inner boot lid sections, and steering components. In North America, the GMC full-sized Savana and Chevrolet Express vans use up to 26.0 kg of magnesium alloy.

**Caliper Mounting Bracket**: The mass reduction ideas for the caliper mounting bracket are to first normalize to the 2002 Chevrolet Avalanche 1500 and then change the component material from cast iron to cast magnesium. The individual baseline component mass was 2.18 kg and the redesign mass was 0.69 kg, resulting in an overall mass savings of 2.98 kg (68.3%) for the two brackets compared to the steel units.

The major components contributing to the mass reduction within the Rear Rotor/Drum and Shield Subsystem are the rear drum, backing plate, and the wheel cylinder housing.

**Rear Drum**: The mass reduction idea for the rear drum is a combination of two different changes to the baseline design. These changes include changing the baseline material from cast iron to aluminum metal matrix composite and adding cooling fins on the external surface. The individual baseline component mass was 11.1 kg with the redesign mass 4.2 kg, resulting in an overall mass savings of 13.69 kg (64.1%) for the two drums compared to the baseline units.

**Backing Plate**: The mass reduction idea for the backing plate involved changing the baseline material from steel to cast aluminum. The individual baseline component mass was 2.9 kg, while the redesign mass was 2.19 kg, resulting in an overall mass savings of 1.41 kg (24.3%) for both backing plates compared to the steel units.

**Wheel Cylinder Housing**: The mass reduction idea for the wheel cylinder housing was to change the baseline material from cast iron to cast aluminum. The individual baseline component mass was 0.46 kg, while the redesign mass was 0.23 kg, an overall mass savings of 0.46 kg (50.0%) for both cylinder housings compared to the cast iron units.

The major component contributing to the mass reduction within the Parking Brake and Actuation Subsystem was the park brake lever and frame.

**Park Brake Lever and Frame**: The mass reduction idea for the park brake lever and frame is to change the parking brake mounting frame, cover plate, and lever from stamped steel to cast magnesium. The baseline mass for all three components was 1.61 kg and the redesign mass was 0.68 kg, providing an overall mass savings of 0.93 kg (57.8%) compared to the stamped steel units.

The major components contributing to the mass reduction within the Brake Actuation Subsystem were the brake pedal arm, brake pedal frame, and brake pedal bracket.

**Brake Pedal Arm**: The mass reduction idea for the brake pedal arm is to change the baseline component material from stamped steel to glass filled nylon. The total baseline mass was 1.5 kg while the redesign mass was 0.75 kg, resulting in an overall mass savings of 0.75 kg (50.0%) compared to the steel unit.

**Brake Pedal Frame**: The mass reduction idea for the brake pedal frame is to change it from a multi-piece stamped steel welded construction to a cast magnesium design. The baseline mass was 1.7 kg with the redesign mass 0.72 kg, resulting in an overall mass savings of 0.98 kg (57.6%).

**Brake Pedal Bracket Assembly**: The mass reduction idea for the brake pedal bracket assembly was to change the side plates, which are fabricated from stamped steel, to cast magnesium. The baseline assembly had a mass of 1.54 kg versus the redesigned assembly mass of 0.98 kg, resulting in an overall mass savings of 0.56 kg (36.4%).

The major component contributing to the mass reduction within the Power Brake Subsystem was the vacuum booster assembly.

**Vacuum Booster Assembly**: The mass reduction ideas for the vacuum booster assembly affected each internal plate as well as the outer housings. These ideas included changing the front housing, rear housing, front backing plate, and the spacer ring from stamped steel to cast magnesium. The rear backing plate idea changed the baseline material from stamped steel to stamped aluminum. The actuator shaft changed from steel to titanium and the mounting studs from steel to aluminum. The baseline booster unit had a mass of 4.2 kg and the redesign mass was 2.7 kg, resulting in an overall mass savings of 1.5 kg (35.7%) compared to the steel unit.

### 3.2.9 Exhaust System Overview

This following section identifies mass reduction alternatives and cost implications for the Exhaust System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). Not including secondary mass savings, the exhaust system mass was reduced by 6.34 kg (16.52%). This increased the cost by $19.54, or $3.08 per kg. Mass reduction for this system reduced vehicle curb weight by 0.27%. With secondary mass savings, the additional mass savings was 0.605 kg for a total system mass reduction of 6.95 kg (0.29% curb weight reduction). The increase in costs were reduced by $5.85 due to secondary mass savings resulting in a total system cost increase of $13.69 or $1.97 per kg.

**Table 3.2-9** provides a summary of mass reduction and cost impact for select sub-subsystems evaluated. The table does not include secondary mass savings and associated cost benefits. The additional benefits of secondary mass savings are included in the detailed Exhaust System review (Section 4.9).

**Table 3.2-9: Exhaust System Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 09 | 00 | 00 | Exhaust System | | | | | | | | |
| 09 | 01 | 00 | Acoustical Control Components | 6.34 | 0.605 | 6.95 | -$19.54 | $5.85 | -$13.69 | -$1.97 | 0.29% |
| | | | | **6.34** (Decrease) | **0.605** (Decrease) | **6.95** (Decrease) | **-$19.54** (Increase) | **$5.85** (Decrease) | **-$13.69** (Increase) | **-$1.97** (Increase) | **0.29%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the exhaust system were the muffler and the down pipe.

**Cross Over Pipe Assembly**: The mass reduction idea for the cross over pipe is to change the component material from 409 stainless steel with a wall thickness of 1.9 mm to 304 stainless steel and a wall thickness of 1.2 mm. The individual baseline component mass was 4.23 kg, with the redesign mass at 2.77 kg, resulting in an overall mass savings of 1.46 kg (34.5%).

Most common in today's OEM stainless systems, 409 stainless steel can be replaced with 304 stainless steel. The 304 stainless steel allows for a thinner wall thickness, thereby reducing weight. It is, however, more costly than the 409 stainless steel.

**Expansion Clamp Assembly**: The mass reduction ideas for the expansion clamp assembly involved changing the down pipe component material from 409 stainless steel with a wall thickness of 1.9 mm to a 304 stainless steel and a wall thickness of 1.2 mm. The individual baseline component mass was 2.13 kg, while the redesign mass was 1.66 kg resulting in an overall mass savings of 0.47 kg (22%).

Also in this subsystem was the change from the solid steel hanger brackets to hollow 304 stainless steel. The individual baseline component mass was 0.39 kg, while the redesign mass was 0.27 kg, resulting in an overall mass savings of 0.12 kg (31%). The hangers were changed from the EDPM factory hangers to SGF fiber reinforced hangers. The individual baseline component mass was 0.16 kg, with the redesign mass 0.05 kg, which resulted in an overall mass savings of 0.11 kg (71%).

Replacing 409 stainless steel with 304 stainless is widely common in high-performance cars. Hollow hangers are used in OEM vehicles today, while SGF® fiber reinforced hangers are widely used in Europe on factory vehicles today. The subsystem's baseline component mass was 3.80 kg with the redesign mass 3.09 kg, resulting in an overall mass savings of 0.71 kg (18%).

**Muffler Assembly**: The mass reduction ideas for the muffler assembly were to change the muffler skin, end plates and muffler pipe component material from aluminized steel with a wall thickness of 1.4mm to a 304 stainless steel and a wall thickness of 1 mm The individual baseline component mass is 11.29 kg and the redesign mass is 7.81 kg resulting in an overall mass savings of 3.48 kg or 30%.

Also in this subsystem is the change from the solid steel hanger brackets to hollow 304 stainless steel hanger brackets. The individual baseline component mass was 1.14 kg, with the redesign mass 0.71 kg, resulting in an overall mass savings of 0.35 kg (31%). The hangers were changed from the EDPM factory hangers to SGF fiber reinforced hangers. The individual baseline component mass is 0.477 kg and the redesign mass is 0.13 kg, resulting in an overall mass savings of 0.34 kg (71%).

Using 304 stainless steel to replace 409 stainless steel is widely used in high performance cars. As in the expansion clamp assembly, hollow hangers are used in OEM vehicles today, while SGF fiber reinforced hangers are widely used in Europe. The subsystem's baseline component mass was 19.03 kg and the redesign mass was 14.86 kg, resulting in an overall mass savings of 4.16 kg (22%).

### 3.2.10 Fuel System Overview

This following section identifies mass reduction alternatives and cost implications for the Fuel System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). Not including secondary mass savings, the fuel system mass was reduced by 1.61 kg (6.10%). This decreased the cost by $3.25, or $2.02 per kg. Mass reduction for this system reduced vehicle curb weight by .07%. With secondary mass savings, the additional mass savings was 5.73 kg for a total system mass reduction of 7.34 kg (0.30% curb weight reduction). The decrease in costs was reduced by $8.67 due to secondary mass savings resulting in a total system cost decrease of $11.92, or $1.62 per kg.

**Table 3.2-10** provides a summary of mass reduction and cost impact for select sub-subsystems evaluated. The table does not include secondary mass savings and associated cost benefits. The additional benefits of secondary mass savings are included in the detailed Fuel System review (Section 4.10).

**Table 3.2-10: Fuel System Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 00 | 00 | **Fuel System** | | | | | | | | |
| 10 | 01 | 00 | Fuel Tank and Lines Subsystem | 0.731 | 5.730 | 6.46 | $2.36 | $8.67 | $11.03 | $1.71 | 0.26% |
| 10 | 02 | 00 | Fuel Vapor Management Subsystem | 0.876 | 0.00 | 0.88 | $0.89 | $0.00 | $0.89 | $1.02 | 0.04% |
| | | | | **1.61** (Decrease) | **5.73** (Decrease) | **7.34** (Decrease) | **$3.25** (Decrease) | **$8.67** (Decrease) | **$11.92** (Decrease) | **$1.62** (Decrease) | **0.30%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the fuel system are the vapor canister support on the frame and the fuel line bracket.

**Vapor Canister Support on the Frame**: The mass reduction idea for the vapor canister support on the frame, which is part of the vapor canister subsystem, was to remove the large steel mounting bracket and mounting hardware from the frame, change the bracket material to plastic PP (poly propylene), and mount it to the tank. The vapor canister then mounts to the new plastic mounting bracket by sliding into place. This eliminates the mounting hardware. The individual baseline component mass was 0.71 kg, while the redesign mass was 0.069 kg, resulting in an overall mass savings of 0.64 kg (90%).

This vapor canister mounting style has been used on other GM vehicles, including the Chevrolet Malibu.

**Fuel Line Bracket**: The mass reduction idea for the fuel line bracket that is part of the fuel distribution subsystem was to change the bracket material from steel to plastic PA66 (high-quality poly nylon resin). The individual baseline component mass was 0.21 kg with the redesign mass 0.05 kg, resulting in an overall mass savings of 0.16 kg (74%).

This bracket was not subjected to significant loading (see white paper report). The redesigned plastic bracket with added reinforced ribs will be acceptable for this application.

### 3.2.11 Steering System Overview

This report identifies mass reduction alternatives and cost implications for the Steering System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). **Table 3.2-11** is a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This analysis recorded a system mass reduction of 8.46 kg (26.0%) at a cost increase of $147.46 ($17.44 per kg). The contribution of the steering system to the overall vehicle mass reduction is 0.34%. There are no compounding mass reductions for this system.

**Table 3.2-11: Steering System Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **11** | **00** | **00** | **Steering System** | | | | | | | | |
| 11 | 01 | 00 | Steering Gear | -1.47 | 0.00 | -1.47 | -$247.24 | $0.00 | -$247.24 | $168.57 | -0.06% |
| 11 | 02 | 00 | Power Steering Pump | 5.44 | 0.00 | 5.44 | $40.69 | $0.00 | $40.69 | $7.48 | 0.22% |
| 11 | 03 | 00 | Power Steering Equipment | 1.01 | 0.00 | 1.01 | $54.32 | $0.00 | $54.32 | $53.73 | 0.04% |
| 11 | 04 | 00 | Steering Column Assy | 3.47 | 0.00 | 3.47 | $4.76 | $0.00 | $4.76 | $1.37 | 0.14% |
| | | | | **8.46** (Decrease) | **0.00** | **8.46** (Decrease) | **-$147.46** (Increase) | **$0.00** | **-$147.46** (Increase) | **-$17.44** (Increase) | **0.34%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the Steering Subsystem are the oil pump, steering equipment, and steering column.

**Steering Gear**: The industry trend is to use electric assist in most vehicles and trucks with few exceptions. The individual baseline component mass was 13.9 kg and the redesign mass was 15.4 kg, resulting in an overall mass increase of 1.47 kg (0.06%)

compared to the hydraulic unit. Using the electric steering facilitates weight reduction in other areas of the system that will be discussed.

Electric power steering (EPS) is more efficient than the hydraulic power steering, since the electric power steering motor only needs to provide assistance when the steering wheel is turned, whereas the hydraulic pump must run constantly. The amount of assistance in EPS is easily tunable to the vehicle type, road speed, and even driver preference. Electrical assistance is not lost when the engine fails or stalls, whereas hydraulic assistance stops working if the engine stops, increasing steering effort as the driver must now turn not only the very heavy steering — without any help — but also the power-assistance system itself.

**Power Steering Pump**: The mass reduction idea for the steering pump was to eliminate it completely. The individual baseline component mass was 5.44 kg and the eliminating the unit resulted in an overall mass savings of 5.44 kg , or 100% compared to the hydraulic units.

Selecting an EPS is the latest technology, which is used in a variety of current production vehicles.

**Power Steering Tube Assembly**: The mass reduction idea for the power steering tube assemblies was to eliminate them completely. The individual baseline component mass was 0.65 kg and eliminating the components resulted in an overall mass savings of 0.65 kg, or 100% compared to the steel and rubber tubes.

**Heat Exchanger Assembly**: The mass reduction idea for the heat exchanger was to eliminate it completely. The individual baseline component mass was 0.36 kg and eliminating the components resulted in an overall mass savings of 0.36 kg for the entire system (100%).

**Steering Column**: The mass reduction idea for the steering column is to change the base component material from steel to magnesium. The individual baseline component mass is 10.2 kg and the redesign mass is 13.4 kg resulting in an overall mass savings of 3.25 kg for the column or 32% compared to the steel units.

The 2009 Ford F-150 steering column was more than 60% magnesium based on volume, and represents a greater than 40% weight savings over the prior model steering column. The weight saved was realized through the integration of several components, such as the steel main tube and several brackets that were previously welded together, as well as aluminum support castings that were bolted on, which were integrated into a single magnesium die casting. Utilizing die-cast magnesium also facilitated the integration of optional construction for the engineered steering column energy absorption features. This allowed Ford and Delphi Steering engineers to optimize the steering column's contribution to driver-side vehicle crash safety.

### 3.2.12 Climate Control System Overview

This report details FEV's analysis and results relative to the Climate Control System to identify design concepts, cost effectiveness, and manufacturing feasibility that can meet the function and performance of the baseline vehicle (2011 Chevrolet Silverado). **Table 3.2-12** is a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated.

The Climate Control Subsystem contributed a system mass reduction of 1.94 kg, (9.55%). This mass reduction provided a vehicle cost saving of $14.71, which equated to $7.59 per kg. The overall vehicle mass reduction contribution is 0.08%. **Table 3.2-12** is a summary of the calculated mass reduction and cost impact for each vehicle subsystem evaluated. There are no compounding mass reductions for this system.

**Table 3.2-12: Climate Control System Mass Reduction Summary**

| | | | | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| | | | 2454 | | | | | | | | |
| 12 | 00 | 00 | Climate Control System | | | | | | | | |
| 12 | 01 | 00 | Air Handling / Body Ventilation Subsystemm | 1.94 | 0.00 | 1.94 | $14.71 | $0.00 | $14.71 | $7.59 | 0.08% |
| 12 | 02 | 00 | Heating / Defrosting Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 12 | 03 | 00 | Refrigeration / Air Conditioning Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 12 | 04 | 00 | Controls Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| | | | | **1.94** (Decrease) | **0.00** | **1.94** (Decrease) | **$14.71** (Decrease) | **$0.00** | **$14.71** (Decrease) | **$7.59** (Decrease) | **0.08%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The Climate Control System is very small in package size and weight due to the extensive use of plastics in its components. The only subsystem contributing to the mass reduction in this system was the Air Handling/Body Ventilation Subsystem.

**Air Handling / Body Ventilation Subsystem:** Mucell® and Azote®, both provided by Zotefoams PLC, were employed to attain the mass reduction within this analysis. The mass reduction in both of these materials was achieved through a change in the density of the material by Mucell of 10% to 30%. Azote replaced high-density polyethylene (HDPE) in most applications. The density of regular HDPE is 0.95 g/cm$^3$. Depending on the grade, high-density HDPE Azote can have a density between 0.030 and 0.115 g/cm$^3$.

One of the major advantages of using Mucell is the cycle time gain of 20% to 30% per machine depending on base material. The use of material with a lower density may also transfer to the use of lower tonnage machines for manufacturing, which could become a major competitive cost variable.

Within many of the Air Handling/Body Ventilation Subsystem components there was a need for strength and stiffness due to the fact these components were used as the mounting face for other under-dash products. These applications must be evaluated on a case-by-case basis to understand if Mucell is appropriate. The Azote product has extremely limited mechanical properties and, therefore, cannot be used for applications where mechanical properties are required.

### 3.2.13 Info, Gage, and Warning Device Systems Overview

This report identifies mass reduction alternatives and cost implications for the Information, Gage, and Warning Device System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). In **Table 3.2-13** is a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This project recorded a system mass reduction of 0.248 kg (15.72%) at a cost decrease of $0.66 ($2.66 per kg). Furthermore, the contribution of the Information, Gage, and Warning Device System to the overall vehicle mass reduction is 0.01%. There are no compounding mass reductions for this system.

**Table 3.2-13: Information, Gage, and Warning Device System Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction | | | | | | | |
| 13 | 00 | 00 | **Info,Gage and Warning system** | | | | | | | | |
| 13 | 01 | 00 | Driver Information Module (Instrument Cluster) | 0.06 | 0.00 | 0.06 | $0.49 | $0.00 | $0.49 | $7.67 | 0.00% |
| 13 | 02 | 00 | Traffic Horns (Electric) | 0.18 | 0.00 | 0.18 | $0.17 | $0.00 | $0.17 | $0.93 | 0.01% |
| | | | | **0.25** (Decrease) | **0.00** | **0.25** (Decrease) | **$0.66** (Decrease) | **$0.00** | **$0.66** (Decrease) | **$2.66** (Decrease) | **0.01%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The mass reduction for this system was to change the horn covers from metal to plastic. The mass was reduced 16% but overall contribution level to vehicle reduction was limited. Please reference internal **Info, Gage, and Warning Device Systems** section for details.

### 3.2.14 Electrical Power Supply System Overview

This report identifies mass reduction alternatives and cost implications for the Electrical Power Supply System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). **Table 3.2-14** is a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This project recorded a system mass reduction of 12.81 kg (60.6%) at a cost increase of $172.73, or $13.49 per kg. The contribution of the Electrical Power Supply System to the overall vehicle mass reduction is 0.52%. There are no compounding mass reductions for this system.

**Table 3.2-14: Electrical Power Supply System Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 00 | 00 | **Electrical Power Supply System** | | | | | | | | |
| 14 | 01 | 00 | Service Battery Subsystem | 12.81 | 0.00 | 12.81 | -$172.73 | $0.00 | -$172.73 | -$13.49 | 0.52% |
| | | | | **12.81** (Decrease) | **0.00** | **12.81** (Decrease) | **-$172.73** (Increase) | **$0.00** | **-$172.73** (Increase) | **-$13.49** (Increase) | **0.52%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the Electrical Power Supply System are the battery, battery tray, and auxiliary battery tray.

**Battery**: The mass reduction idea for the battery is to change the traditional lead acid battery to a lithium ion battery. The individual baseline component mass is 17.7 kg and the redesign mass is 5.90 kg resulting in an overall mass savings of 11.8 kg (66%).

The replacement of the lead acid battery with a lithium ion battery is occurring mostly in the recreational vehicle and motorcycle markets today, and the use of this technology is now crossing over into the passenger vehicle market.

**Battery Tray**: The mass reduction idea for the battery tray is to change the base bracket material from steel to PP-GF30 (poly propylene with 30% glass-filled). The individual baseline component mass was 1.94 kg, while the redesign mass was 1.28 kg, resulting in an overall mass savings of 0.66 kg (34%).

This type of battery tray has been used on other vehicles, such as the Ford F-150.

**Auxiliary Battery Tray**: The mass reduction idea for the battery tray is to change the base bracket material from steel to PP-GF30 (poly propylene with 30% glass filled). The individual baseline component mass was 0.98 kg, while the redesign mass was 0.64 kg, resulting in an overall mass savings of 0.33 kg (34%).

This type of battery tray has been used on other vehicles, again, such as the Ford F-150.

### 3.2.15 Lighting System Overview

This report identifies mass reduction alternatives and cost implications for the Lighting System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). **Table 3.2-15** is a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This project recorded a system mass reduction of 0.39 kg (4%) with a cost increase of $2.00, or $5.18 per kg. The contribution of the Lighting System to the overall vehicle mass reduction was 0.02%. There are no compounding mass reductions for this system.

**Table 3.2-15: Lighting System Mass Reduction Summary**

| | | | | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 17 | 00 | 00 | Front Lighting | | | | | | | | |
| 17 | 01 | 00 | Front Lighting Subsystem | 0.386 | 0.00 | 0.386 | -$2.00 | $0.00 | -$2.00 | -$5.18 | 0.02% |
| 17 | 02 | 00 | Interior Lighting Subsystem | 0.000 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 17 | 03 | 00 | Rear Lighting Subsystem | 0.000 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 17 | 04 | 00 | Lighting - Special Mechanisms Subsystem | 0.000 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 17 | 05 | 00 | Light Switches Subsystem | 0.000 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| | | | | **0.386** (Decrease) | **0.00** | **0.386** (Decrease) | **-$2.00** (Increase) | **$0.00** | **-$2.00** (Increase) | **-$5.18** (Increase) | **0.02%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The minimal mass reduction for this system was completed by using the Mucell® gas-injection molding process on the front light housings, and to replacing the front light inner reflectors with Sabic® Ulten. Please reference the **Lighting System** section for details.

### 3.2.16 Electrical Distribution and Electronic Control System Overview

This report identifies mass reduction alternatives and cost implications for the Electrical Distribution and Electronic Control System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado). **Table 3.2-16** contains a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This project recorded a system mass reduction of 8.47 kg (25.2%) at a cost decrease of $61.44 ($7.26 per kg). Furthermore, the contribution of the electrical distribution and electronic control system to the overall vehicle mass reduction was 0.35%. There are no compounding mass reductions for this system.

**Table 3.2-16: Electrical Distribution and Electronic Control System Mass Reduction Summary**

| | | | | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| | | | 2454 | | | | | | | | |
| **18** | **01** | **00** | **Electrical Wiring and Circuit Protection Subsystem** | | | | | | | | |
| 18 | 01 | 01 | Front End and Engine Compartment Wiring | 1.50 | 0.00 | 1.50 | $15.34 | $0.00 | $15.34 | $10.25 | 0.06% |
| 18 | 01 | 02 | Instrument Panel Harness | 1.70 | 0.00 | 1.70 | $15.91 | $0.00 | $15.91 | $9.34 | 0.07% |
| 18 | 01 | 03 | Body and Rear End Wiring | 0.954 | 0.00 | 0.954 | $9.37 | $0.00 | $9.37 | $9.82 | 0.04% |
| 18 | 01 | 04 | Trailer Tow Wiring | 1.42 | 0.00 | 1.42 | $13.91 | $0.00 | $13.91 | $9.82 | 0.06% |
| 18 | 01 | 05 | Battery Cables | 0.503 | 0.00 | 0.503 | $6.94 | $0.00 | $6.94 | $13.79 | 0.02% |
| 18 | 01 | 06 | Load Compartment Fuse Box / Passive | 0.274 | 0.00 | 0.274 | -$0.80 | $0.00 | -$0.80 | -$2.92 | 0.01% |
| 18 | 01 | 07 | Interior & Console wiring | 0.667 | 0.00 | 0.667 | $0.77 | $0.00 | $0.77 | $1.15 | 0.03% |
| 18 | 01 | 08 | Frt & Rear door harness | 1.45 | 0.00 | 1.45 | $0.00 | $0.00 | $0.00 | $0.00 | 0.06% |
| | | | | | | | | | | | |
| | | | | **8.47** (Decrease) | **0.00** | **8.47** (Decrease) | **$61.44** (Decrease) | **$0.00** | **$61.44** (Decrease) | **$7.26** (Decrease) | **0.35%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the Electrical Distribution and Electronic Control System were the instrument panel harness and under frame/tow harness.

**Instrument Panel Harness**: The mass reduction idea for the instrument panel harness was to change the base copper wire material to aluminum wire and the wire sheathing from PVC (polyvinyl chloride) to PPO (polyphenylene oxide) material. The individual baseline component mass was 5.24 kg. The redesign mass was 3.82 kg, which produced an overall mass savings of 1.41 kg (48%).

Aluminum wire and PPO sheathing are currently being tested in vehicles on road by Lear® Corporation. Sumitomo® Corporation has developed an aluminum wire harness that is used in the 2010 Toyota Ractis and in the 2011 Toyota Yaris.

**Under Frame/Tow Harness**: The mass reduction idea for the under frame/tow harness was to change the base copper wire material to aluminum wire and change the wire sheathing from PVC to PPO material. The individual baseline component mass was 5.22 kg. The redesign mass was 3.81 kg, which resulted in an overall mass savings of 1.41 kg, or 48%.

Similar to the instrument panel harness, aluminum wire and PPO sheathing is also being road tested by Lear for this harness. Likewise, Sumitomo has an aluminum wire harness used in the 2010 Toyota Ractis and the 2011 Toyota Yaris.

### 3.2.17 Body and Frame Systems Overview

This report details EDAG's work and findings relative to the Body Group -A- and Frame & Mounting Systems to prove the design concept, cost effectiveness, and manufacturing feasibility that can meet the function and performance of the baseline vehicle (2011 Chevrolet Silverado). **Table 3.2-17** is a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This project recorded a combined system mass reduction of 27.6% (230.1 kg system mass reduction) at a cost increase of $5.43 per kg ($1,250.12 increase). Furthermore, the contribution of both systems to the overall vehicle mass reduction is 9.6%.

**Table 3.2-17: Body Group -A- System / Frame & Mounting System Mass Reduction Summary**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC "$" (2) | Average Cost/ Kilogram "$/kg" (2) | Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| **03** | **00** | **00** | **Body System Group -A-** | **567.40** | **206.40** | **-1195.70** | **-5.79** | **36.38%** | **8.65%** |
| **03** | **01** | **00** | **Body Structure Subsystem** | **207.20** | **75.40** | **-506.61** | **-6.72** | **36.39%** | **3.16%** |
| 03 | 01 | 01 | Cabin | 207.20 | 75.40 | -506.61 | -6.72 | 36.4% | 3.16% |
| **03** | **02** | **00** | **Front End Subsystem** | **31.00** | **11.60** | **-62.92** | **-5.42** | **37.42%** | **0.49%** |
| 03 | 02 | 01 | Radiator Asm | 12.90 | 5.70 | -10.36 | -1.82 | 44.2% | 0.24% |
| 03 | 02 | 02 | Radiator Support | 12.10 | 5.90 | -52.56 | -8.91 | 48.8% | 0.25% |
| 03 | 02 | 12 | Tow Hooks | 2.25 | 0.00 | 0.00 | 0.00 | 0.0% | 0.00% |
| 03 | 02 | 13 | Hood Hinges | 3.75 | 0.00 | 0.00 | 0.00 | 0.0% | 0.00% |
| **03** | **03** | **00** | **Body Closure Subsystem** | **153.70** | **60.00** | **-288.90** | **-4.82** | **39.04%** | **2.51%** |
| 03 | 03 | 01 | Panel Fender Outer LH | 14.90 | 7.50 | -19.34 | -2.58 | 50.3% | 0.31% |
| 03 | 03 | 01 | Panel Fender Outer RH | 14.00 | 7.00 | -18.21 | -2.60 | 50.0% | 0.29% |
| 03 | 03 | 02 | Hood | 22.70 | 11.00 | -35.19 | -3.20 | 48.5% | 0.46% |
| 03 | 03 | 03 | Door Asm, Front LH | 29.00 | 10.20 | -58.99 | -5.78 | 35.2% | 0.43% |
| 03 | 03 | 03 | Door Asm, Front RH | 28.90 | 10.10 | -58.73 | -5.81 | 34.9% | 0.42% |
| 03 | 03 | 04 | Door Asm, Rear LH | 22.00 | 7.00 | -49.31 | -7.04 | 31.8% | 0.29% |
| 03 | 03 | 04 | Door Asm, Rear RH | 22.20 | 7.20 | -49.14 | -6.83 | 32.4% | 0.30% |
| **03** | **19** | **00** | **Bumpers Subsystem** | **48.40** | **16.40** | **-69.71** | **-4.25** | **33.88%** | **0.69%** |
| 03 | 19 | 01 | Bumper Front | 28.50 | 9.90 | -23.68 | -2.39 | 34.7% | 0.41% |
| 03 | 19 | 02 | Bumper Rear | 19.90 | 6.50 | -46.03 | -7.08 | 32.7% | 0.27% |
| **03** | **26** | **00** | **Cargo Box Subsystem** | **127.10** | **43.00** | **-267.56** | **-6.22** | **33.83%** | **1.80%** |
| 03 | 26 | 01 | Cargo Box | 108.30 | 34.40 | -241.46 | -7.02 | 31.8% | 1.44% |
| 03 | 26 | 02 | Tailgate | 18.80 | 8.60 | -26.10 | -3.03 | 45.7% | 0.36% |
| **07** | **00** | **00** | **Frame & Mounting System** | **267.64** | **23.70** | **-54.42** | **-2.30** | **8.86%** | **0.99%** |
| **07** | **01** | **00** | **Frame Subsystem** | **252.27** | **23.70** | **-54.42** | **-2.30** | **9.39%** | **0.99%** |
| 07 | 01 | 01 | Front Cross Member | 4.90 | 1.60 | -3.67 | -2.30 | 32.7% | 0.07% |
| 07 | 01 | 01 | Trans Cross Member | 4.90 | 1.60 | -3.67 | -2.30 | 32.7% | 0.07% |
| 07 | 01 | 01 | Other Components… | 232.20 | 20.50 | -47.07 | -2.30 | 8.8% | 0.86% |
| 07 | 01 | 03 | Body Isolators | 10.27 | 0.00 | 0.00 | 0.00 | 0.0% | 0.00% |
| **07** | **03** | **00** | **Engine Transmission Mounting Subsystem** | **2.14** | **0.00** | **0.00** | **0.00** | **0.00%** | **0.00%** |
| 07 | 03 | 02 | Transmission Mount | 2.14 | 0.00 | 0.00 | 0.00 | 0.0% | 0.00% |
| **07** | **04** | **00** | **Towing and Coupling Attachments Subsystem** | **13.23** | **0.00** | **0.00** | **0.00** | **0.00%** | **0.00%** |
| 07 | 04 | 01 | Towing Provisions | 13.23 | 0.00 | 0.00 | 0.00 | 0.0% | 0.00% |
| | | | | | | | | | |
| | | | | **835.04** | **230.10** (Decrease) | **-1,250.12** (Increase) | **-5.43** (Increase) | **27.56%** | **9.64%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

*NOTE: Only sub-subsystems with significant mass reduction are shown in detail. Total values (bold) at the system and sub-system level include all sub-subsystem mass reduction*

The major components contributing to the mass reduction within the **Body Structure Subsystem** is the cabin.

**Cabin**: The mass reduction ideas for the optimized cabin were to stamp, rivet, and bond aluminum sheet (5 series) and gauge size structures with castings at some of the highly loaded interfaces. The cabin baseline mass was 207 kg and the redesign mass was 132 kg. This resulted in an overall mass savings of 75 kg (36%).

The major components contributing to the mass reduction within the **Front End Subsystem** are the radiator assembly and radiator support.

**Radiator Assembly**: The mass reduction idea for the radiator assembly was to change the base component material from steel to aluminum. The baseline mass was 12.9 kg and the redesign mass was 7.2 kg, resulting in an overall mass savings of 5.7 kg (44%).

**Radiator Support**: The mass reduction idea for the radiator support was to change the base component material from steel to aluminum. The baseline mass was 12.1 kg and the redesign mass was 6.2 kg, resulting in an overall mass savings of 5.9 kg (49%).

The major components contributing to the mass reduction within the **Body Closure Subsystem** are the panel fenders, hood, and door assemblies.

**Outer Panel Fender, LH and RH**: The mass reduction idea for the redesigned panel fender was to stamp it out of aluminum optimized for grade and gauge size. The panel fenders baseline mass totaled 28.9 kg while the redesign mass totaled 14.4 kg. This resulted in an overall mass savings of 14.5 kg (50%).

**Hood**: The mass reduction idea for the redesigned hood was to stamp it out of aluminum optimized for grade (6022) and gauge sizes. The baseline hood mass totaled 22.7 kg while the redesign mass is 11.7 kg, resulting in an overall mass savings of 11 kg (48%).

**Door Assembly, Front LH and RH**: The mass reduction ideas for the redesigned front doors were to stamp them from aluminum sheet optimized for grade (6022) and gauge sizes. The front doors baseline mass totals 58 kg while the redesign mass totals 38 kg, resulting in an overall mass savings of 20 kg, or 35%.

**DoorAssembly, Rear LH and RH**: The mass reduction ideas for the redesigned rear doors were to stamp them out of aluminum sheet optimized for grade (6022) and gauge sizes. The rear doors baseline mass totals 44 kg, while the redesign mass totals 30 kg resulting in an overall mass savings of 14 kg, or 32%.

The major components contributing to the mass reduction within the **Bumper Subsystem** are the front and rear bumpers.

**Front Bumper**: The mass reduction idea for the redesigned front bumper was to stamp it out of aluminum sheet optimized for grade (6022-T6) and gauge sizes. The baseline front bumper mass was 29 kg. The redesign mass was 19 kg resulting in an overall mass savings of 10 kg, or 35%.

**Rear Bumper**: The mass reduction idea for the redesigned rear bumper was to stamp it out of aluminum sheet optimized for grade (6013-T6) and gauge sizes. The baseline rear bumper mass was 20 kg while the redesign mass was 13 kg, resulting in an overall mass savings of 7 kg (35%).

The major components contributing to the mass reduction within the **Cargo Box Subsystem** is the cargo box assembly and the tailgate.

**Cargo Box**: The mass reduction idea for the optimized cargo box was to stamp the panels out of aluminum grade sheet optimized for grade (5 series) and gauge sizes. The cargo box baseline mass was 108 kg and the redesign mass was 74 kg, resulting in an overall mass savings of 34 kg (31%).

**Tailgate**: The mass reduction ideas for the redesigned tailgate was to stamp it from aluminum sheet optimized for grade (6022) and gauge sizes. The tailgate baseline mass totaled 19 kg while the redesign mass totaled 10 kg, resulting in an overall mass savings of 9 kg (46%).

The major component contributing to the mass reduction within the **Frame Subsystem** for the **Frame and Mounting System** is the frame assembly.

**Frame Assembly**: The mass reduction ideas for the redesigned frame assembly made use of tailor rolled blanks which utilized an optimized high-strength and advanced high-strength steel. The two front cross-over members utilized an aluminum sheet optimized for grade (6082) and gauge size. The frame assembly baseline mass totaled 242 kg, while the redesign mass totaled 218 kg. This resulted in an overall mass savings of 24 kg (10%).

# 4. Mass Reduction and Cost Analysis – Vehicle Systems White Papers

## 4.1 Engine System

The Chevrolet Silverado selected as the subject of this study came equipped with a 5.3 Liter V8 producing 315 horse power and 335 ft.-lbs of torque. Designated by Chevrolet as its LC9 variant, this engine features cylinder deactivation and is flex-fuel compatible. Other features include aluminum deep skirt, closed deck block with cast-in liners and 6 bolt mains. The cam-in-block pushrod design has been outfitted with a phaser enabling variable valve timing. This naturally aspirated, port-injected layout utilizes a single runner intake manifold. All-aluminum construction and plastic intake manifold are lightweight features already implemented by GM.

Shared applications include the Chevrolet Avalanche, Chevrolet Suburban, GMC Sierra, and GMC Yukon XL. Base construction of the engine was launched in 2005 as the fourth-generation small block produced by General Motors.[25]

Simultaneous with this study was the technical release of the new fifth-generation General Motors small block engine. Well-publicized technological improvements included direct injection, new combustion system, and variable displacement oil pump. Mass-reducing features include tapered connecting rods (pin end), core drilled crankshaft journals (mains and rods), and direct mount ignition coils. These features do not offer mass reduction beyond what has been investigated in this study. As shown in the following sections, these same ideas were implemented and integrated with other technologies for additional mass savings.

25 http://en.wikipedia.org/wiki/GM_Vortect_engine


**Image 4.1-1: Silverado Base Engine (5.3Liter LC9)**
*(Source: http://www.gmpowertrain.ca/product.html)*

The Base Engine System comprised 9.78% of the total Silverado vehicle mass. This system was divided into various subsystems as shown in **Table 4.1-1**. Significant mass contributors to the Engine System include the Cylinder Block, Crank Drive, and Cylinder Head Subsystems.

**Table 4.1-1: Baseline Subsystem Breakdown for Engine System**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 00 | 00 | Engine System | |
| 01 | 02 | 00 | Engine Frames, Mounting, and Brackets Subsystem | 6.066 |
| 01 | 03 | 00 | Crank Drive Subsystem | 37.003 |
| 01 | 04 | 00 | Counter Balance Subsystem | 0.000 |
| 01 | 05 | 00 | Cylinder Block Subsystem | 59.864 |
| 01 | 06 | 00 | Cylinder Head Subsystem | 24.902 |
| 01 | 07 | 00 | Valvetrain Subsystem | 16.258 |
| 01 | 08 | 00 | Timing Drive Subsystem | 1.750 |
| 01 | 09 | 00 | Accessory Drive Subsystem | 8.272 |
| 01 | 10 | 00 | Air Intake Subsystem | 11.951 |
| 01 | 11 | 00 | Fuel Induction Subsystem | 1.122 |
| 01 | 12 | 00 | Exhaust Subsystem | 12.166 |
| 01 | 13 | 00 | Lubrication Subsystem | 10.547 |
| 01 | 14 | 00 | Cooling Subsystem | 24.322 |
| 01 | 15 | 00 | Induction Air Charging Subsystem | 0.000 |
| 01 | 16 | 00 | Exhaust Gas Re-circulation Subsystem | 0.050 |
| 01 | 17 | 00 | Breather Subsystem | 0.109 |
| 01 | 60 | 00 | Engine Management, Engine Electronic, Electrical Subsystem | 5.670 |
| 01 | 70 | 00 | Accessory Subsystems (Start Motor, Generator, etc.) | 19.893 |
| | | | | |
| | | | **Total System Mass =** | 239.945 |
| | | | **Total Vehicle Mass =** | 2454 |
| | | | **System Mass Contribution Relative to Vehicle =** | 9.78% |

Materials for all components comprising the Silverado engine are represented in **Figure 4.1-1**. In terms of mass proportion, aluminum was the top material used, followed closely by steel.


| | | Material Categories: |
|---|---|---|
| 40.9% | 98.211 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 43.9% | 105.330 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 1.3% | 3.126 | 6. Rubber |
| 5.8% | 13.892 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 8.1% | 19.385 | 9. Other |
| 100% | 239.945 | TOTAL |

**Figure 4.1-1: Baseline Material Breakdown for Engine System**

**Table 4.1-2** summarizes mass and cost savings by subsystem. The systems largest savings were realized in the Exhaust Subsystem. Significant mass savings were also found in the Cooling, Cylinder Block, and Lubrication Subsystems. Detailed system analysis resulted in 23.8 kg saved at a cost of $114.63, resulting in a $4.82 per kg cost increase. The driver for cost increase came from the Cooling Subsystem featuring an electric water pump.

**Table 4.1-2: Mass Reduction and Cost Impact for Engine System**

| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys./ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction Idea | | | | | |
| 01 | 00 | 00 | **Engine System** | | | | | | |
| 01 | 02 | 00 | Engine Frames, Mounting, and Brackets Subsystem | B | 1.103 | -0.010 | -$0.01 | 18.18% | 0.04% |
| 01 | 03 | 00 | Crank Drive Subsystem | A | 2.376 | 2.952 | $1.24 | 6.42% | 0.10% |
| 01 | 04 | 00 | Counter Balance Subsystem | | 0.000 | 0.000 | $0.00 | 0.00% | 0.00% |
| 01 | 05 | 00 | Cylinder Block Subsystem | A | 3.298 | 0.797 | $0.24 | 5.51% | 0.13% |
| 01 | 06 | 00 | Cylinder Head Subsystem | A | 1.161 | 6.058 | $5.22 | 4.66% | 0.05% |
| 01 | 07 | 00 | Valvetrain Subsystem | A | 0.192 | 0.050 | $0.26 | 1.18% | 0.01% |
| 01 | 08 | 00 | Timing Drive Subsystem | X | 0.415 | -2.442 | -$5.88 | 23.72% | 0.02% |
| 01 | 09 | 00 | Accessory Drive Subsystem | A | 1.732 | 0.727 | $0.42 | 20.94% | 0.07% |
| 01 | 10 | 00 | Air Intake Subsystem | B | 0.941 | -0.542 | -$0.58 | 7.88% | 0.04% |
| 01 | 11 | 00 | Fuel Induction Subsystem | | 0.000 | 0.000 | $0.00 | 0.00% | 0.00% |
| 01 | 12 | 00 | Exhaust Subsystem | A | 3.148 | -20.000 | $0.00 | 25.88% | 0.13% |
| 01 | 13 | 00 | Lubrication Subsystem | D | 3.009 | -11.242 | -$3.74 | 28.53% | 0.12% |
| 01 | 14 | 00 | Cooling Subsystem | X | 3.314 | -92.063 | -$27.78 | 13.63% | 0.14% |
| 01 | 15 | 00 | Induction Air Charging Subsystem | | 0.000 | 0.000 | $0.00 | 0.00% | 0.00% |
| 01 | 16 | 00 | Exhaust Gas Re-circulation Subsystem | | 0.000 | 0.000 | $0.00 | 0.00% | 0.00% |
| 01 | 17 | 00 | Breather Subsystem | | 0.000 | 0.000 | $0.00 | 0.00% | 0.00% |
| 01 | 60 | 00 | Engine Management, Engine Electronic, Electrical Subsystem | A | 0.886 | 1.973 | $2.23 | 15.63% | 0.04% |
| 01 | 70 | 00 | Accessory Subsystems (Start Motor, Generator, etc.) | B | 2.229 | -0.892 | -$0.40 | 11.20% | 0.09% |
| | | | | D | 23.805 (Decrease) | -$114.63 (Increase) | -$4.82 (Increase) | 9.92% | 0.97% |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

Research and development costs, warranty costs, and noise, vibration, and harshness (NVH) were not captured in this analysis.

All of the engine components were reviewed for mass savings opportunities. No viable opportunities were identified for the Fuel Induction, Exhaust Gas Re-circulation, and Breather Subsystems. The Silverado engine had no counter balance or induction air charging components; hence, no mass savings for these subsystems.

This analysis focused on lightweight solutions applied at a component level. The impact of increasing power density through air induction and intelligent valve control have been the subject of prior research and was not investigated for mass savings (downsizing) opportunity in this study.

Downsizing the engine, permissible by reducing the vehicle curb weight, is covered in **Section 4.1.18, Secondary Mass Savings**.

### 4.1.1 Engine Frames, Mounting, and Brackets Subsystem

#### 4.1.1.1 Subsystem Content Overview

As seen below in **Table 4.1-3**, the most significant contributor to the Engine Frames, Mounting, and Brackets Subsystem mass are the Engine Mountings. This subsystem comprises 2.5% of the engine mass.

**Table 4.1-3: Mass Breakdown by Sub-subsystem for Engine Frames, Mounting, and Brackets Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 02 | 00 | Engine Frames, Mounting, and Brackets Subsystem | |
| 01 | 02 | 01 | Engine Frames | 0.000 |
| 01 | 02 | 02 | Engine Mountings | 5.732 |
| 01 | 02 | 10 | Hanging Eyes | 0.334 |
| 01 | 02 | 99 | Misc. | 0.000 |
| | | | | |
| | | | Total Subsystem Mass = | 6.066 |
| | | | Total System Mass = | 239.945 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 2.53% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.25% |

#### 4.1.1.2 Chevrolet Silverado Baseline Subsystem Technology

As pictured in **Image 4.1-2**, the Silverado engine/transmission assembly is secured to the vehicle chassis with three isolating mounts, one at either side of the cylinder block, and one supporting the output end of the transmission.

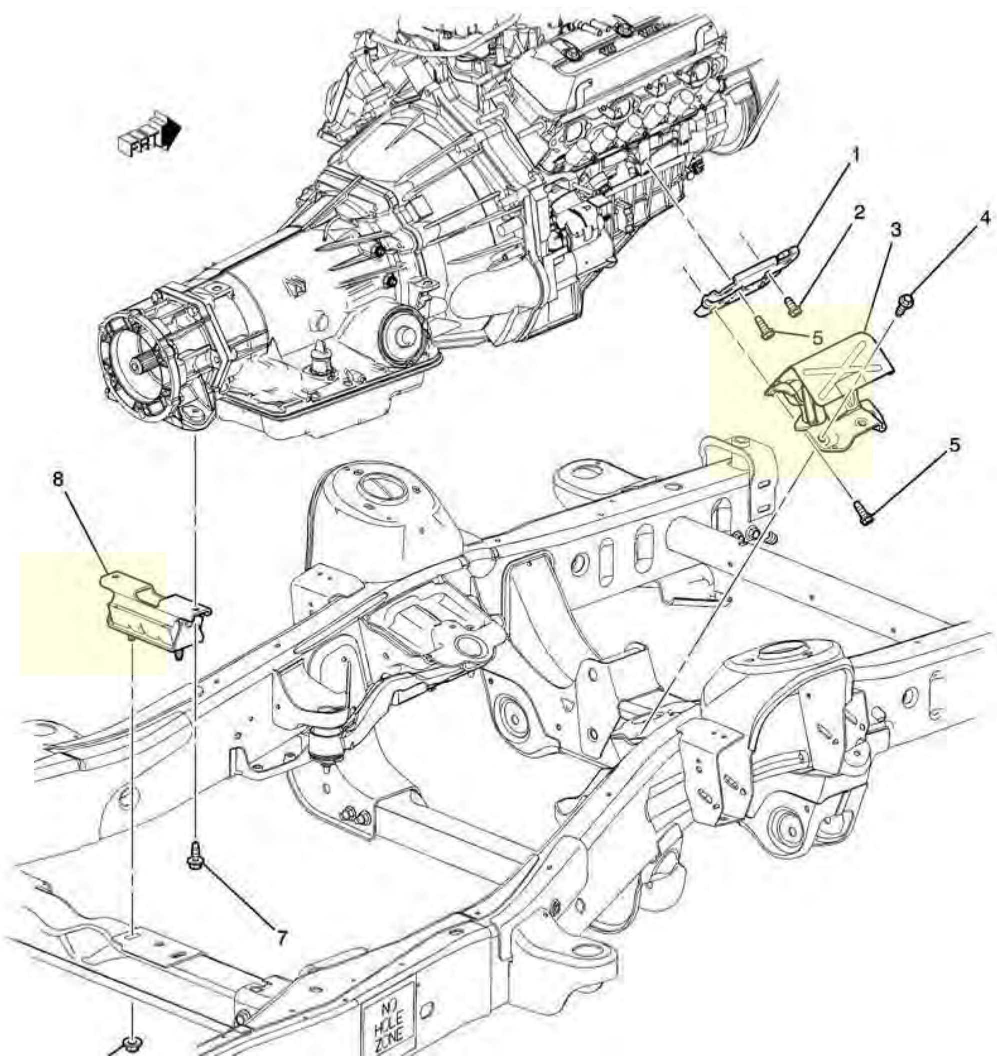


**Image 4.1-2: Silverado Engine Mount Diagram**
*(Source: http://parts.nalleygmc.com)*

The main structure of the Silverado engine mount (**Image 4.1-3**) is made up of three steel stampings. The center stamping, over-molded with rubber, houses oil and a diaphragm valve for improved NVH. The engine lift bracket (**Image 4.1-3**) is a stamped steel weldment bolting to the rear of the engine.

**Image 4.1-3: Silverado Engine Mount and Engine Lift Bracket**
*(Source: FEV, Inc.)*

### 4.1.1.3 Mass Reduction Industry Trends

Engine mounts conventionally made from metal are now being manufactured from plastic. Shown in **Image 4.1-4** is a glass-filled polyamide engine mount designed for specific model versions of Renault-Nissan small and compact cars, as well as electric cars. Plastic in this application saves 25% over metal.

**Image 4.1-4: Polyamide Engine Mount**
*(Source: http://www.zf.com)*

Polyamide torque dampeners are standard on current production Opel Astra/Insignia models (**Image 4.1-5**).[26] BMW 5 Series GT now features a Polyamide rear powertrain mount, saving 50% mass (**Image 4.1-6**). [27]

**Image 4.1-5: (Left) Polyamide Torque Dampener**
*(Source: www.contitech.de)*

**Image 4.1-6: (Right) Polyamide Engine Mount**
*(Source: www.contitech.de)*

Recently, Magnesium has found an application in engine mounts. Magnesium mounts helped the 2013 Cadillac ATS (**Image 4.1-7**) become the lightest vehicle in the U.S. segment.[28]

26 www.contitech.de/pages/produkte/schwingungstechnik/motorlagerung/motorlagerkomponenten_en.html

27 http://wot.motortrend.com/fat-winter-tires-to-plastic-six-surprises-from-continentals-techshow.html

28http://media.gm.com/media/us/en/gm/press_kits.detail.html/content/Pages/news/us/en/2012/May/0510_ats.html

**Image 4.1-7: Magnesium Engine Mount – 2013 Cadillac ATS**
*(Source: http://www.sae.org)*

The 2015 F-150 is expected to launch with high-strength steel engine mounts, which will save mass.

#### 4.1.1.4 Summary of Mass Reduction Concepts Considered

**Table 4.1-4** lists the mass reduction ideas considered for the Engine Frames, Mounting, and Brackets Subsystem. Due to the existing mounting configuration, plastic was considered not strong enough. Quantifying mass savings and cost impact for plastic in this application would require complete redesign and engineering effort beyond the scope of this study. Considering the towing capacity of a full-size truck, this high-load application is not well-suited for plastic at this time. Aluminum or magnesium are a possibility, but would require a larger packaging envelope and present a potential packaging issue. Dual-phase 980 was considered as a high-strength replacement for mild steel, but was eliminated based on forming limitations.

**Table 4.1-4: Summary of Mass Reduction Concepts Considered for the Engine Frames, Mounting, and Brackets Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Engine Mountings | Scale down engine mounts based on reduced powertrain size for reduced curb weight | 7% mass reduction | Some components may cross other product lines |
| Engine Mountings | Material change from Steel to Nylon | 40% mass reduction | Insufficient strength |
| Engine Mountings | Material change from Steel to long fiber compression molding | 40% mass reduction | Insufficient strength |
| Engine Mountings | Material change from Steel to Magnesium | 25% mass reduction | Packaging concern |
| Engine Mountings | Mild steel to DP600 | 25% mass reduction | Formability challenges |
| Engine Mountings | Mild steel to DP980 | 40% mass reduction | Formability challenges |
| Engine Mount Bracket | Mild steel to DP600 | 25% mass reduction | Formability challenges |
| Engine Mount Bracket | Mild steel to DP980 | 40% mass reduction | Formability challenges |
| Engine Lift Bracket | Mild steel to DP600 | 25% mass reduction | Formability challenges |
| Engine Lift Bracket | Mild steel to DP980 | 40% mass reduction | Formability challenges |
| Engine Lift Bracket | Remove after assembly | 100% mass reduction | Serviceability |

#### 4.1.1.5 Selection of Mass Reduction Ideas

**Table 4.1-5** lists the mass reduction ideas applied to Engine Frames, Mounting, and Brackets Subsystem.

**Table 4.1-5: Mass Reduction Ideas Selected for Engine Frames, Mounting, and Brackets Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **02** | **00** | **Engine Frames, Mounting, and Brackets Subsystem** | |
| 01 | 02 | 01 | Engine Frames | N/A |
| 01 | 02 | 02 | Engine Mountings | Mild Steel to AHSS DP600 |
| 01 | 02 | 10 | Hanging Eyes | Remove after assembly |
| 01 | 02 | 99 | Misc. | N/A |
| | | | | |

**Image 4.1-8** shows the components that construct the engine mount. The stampings boxed in blue were changed from mild steel to dual phase 600 high strength steel. High-strength part thickness was calculated using the yield strength ratio between mild steel and DP600 (i.e., 310MPa/400MPa = 0.78). High-strength steel's reduced ductility would likely require redesign of the assembly.

The engine lift bracket (**Image 4.1-9**) is accessible for removal after engine installation. It eliminates the mass of this component and fastener.

**Image 4.1-8: Engine Mount Components**
*(Source: FEV, Inc.)*

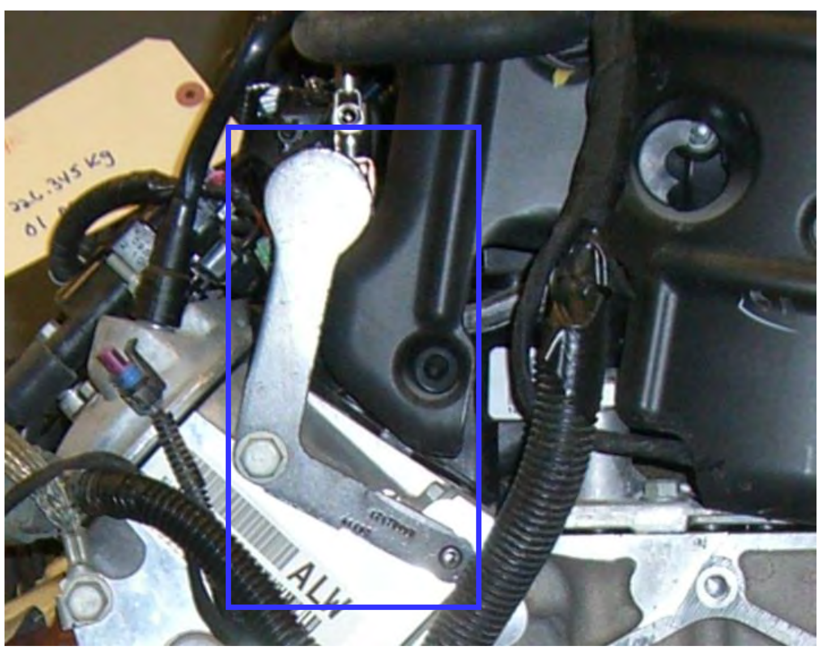

**Image 4.1-9: Engine Lift Bracket**
*(Source: FEV, Inc.)*

#### 4.1.1.6 Calculated Mass Reduction and Cost Impact Results

As shown in **Table 4.1-6**, AHSS applied to the Silverado engine mounts saves mass and cost. Removing the engine lift bracket following engine installation adds an operation to engine assembly and therefore increases cost (see Hanging Eyes Sub-subsystem). Reuse of the engine lift bracket could reduce cost, but this analysis assumes a new bracket is used for each engine installation.

**Table 4.1-6: Mass reduction and Cost Impact for Engine Frames, Mounting, and Brackets Subsystem**

*(See Appendix for Additional Cost Detail)*

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 01 | 02 | 00 | **Engine Frames, Mounting, and Brackets Subsystem** | | | | | | |
| 01 | 02 | 01 | Engine Frames | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 02 | 02 | Engine Mountings | A | 0.769 | $0.29 | $0.38 | 13.41% | 0.03% |
| 01 | 02 | 03 | Hangine Eyes | A | 0.334 | -$0.30 | $0.00 | 100.00% | 0.01% |
| 01 | 02 | 04 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | B | **1.103** (Decrease) | **-0.010** (Increase) | **-$0.01** (Increase) | **18.18%** | **0.04%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.1.2 Crank Drive Subsystem

#### 4.1.2.1 Subsystem Content Overview

As seen in **Table 4.1-7**, the most significant contributor to the Crank Drive Subsystem is the crankshaft, comprising 15.4% of the engine mass. Included in the crankshaft mass is the camshaft drive gear.

**Table 4.1-7: Mass Breakdown by Sub-subsystem for Crank Drive Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 03 | 00 | Crank Drive Subsystem | |
| 01 | 03 | 01 | Crankshaft | 24.005 |
| 01 | 03 | 02 | Flywheel | 2.590 |
| 01 | 03 | 03 | Connect Rods (Assemblies: Connecting Rod, Connecting Rod Cap) | 5.408 |
| 01 | 03 | 04 | Pistons (Assemblies, Including Pistons, Ring Packs, Piston Pins, Circlips) | 5.000 |
| 01 | 03 | 05 | Drive for Accessory Drives (Down force, Flywheel side) | 0.000 |
| 01 | 03 | 10 | Drive for Timing Drive (Down force, Flywheel side) | 0.000 |
| 01 | 03 | 15 | Adaptors | 0.000 |
| 01 | 03 | 99 | Misc. | 0.000 |
| | | | | |
| | | | Total Subsystem Mass = | 37.003 |
| | | | Total System Mass = | 239.945 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 15.42% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.51% |

#### 4.1.2.2 Chevrolet Silverado Baseline Subsystem Technology

Silverado features a cast iron crankshaft with pressed timing target and camshaft drive gear. The connecting rods are powder metal with crack break caps. The near net shape powder metal part does not require balancing. A bronze split type bushing pressed into the connecting rod creates the bearing surface for the floating wrist pin, which is trapped into the piston by circlips. System components are pictured in **Image 4.1-10**.

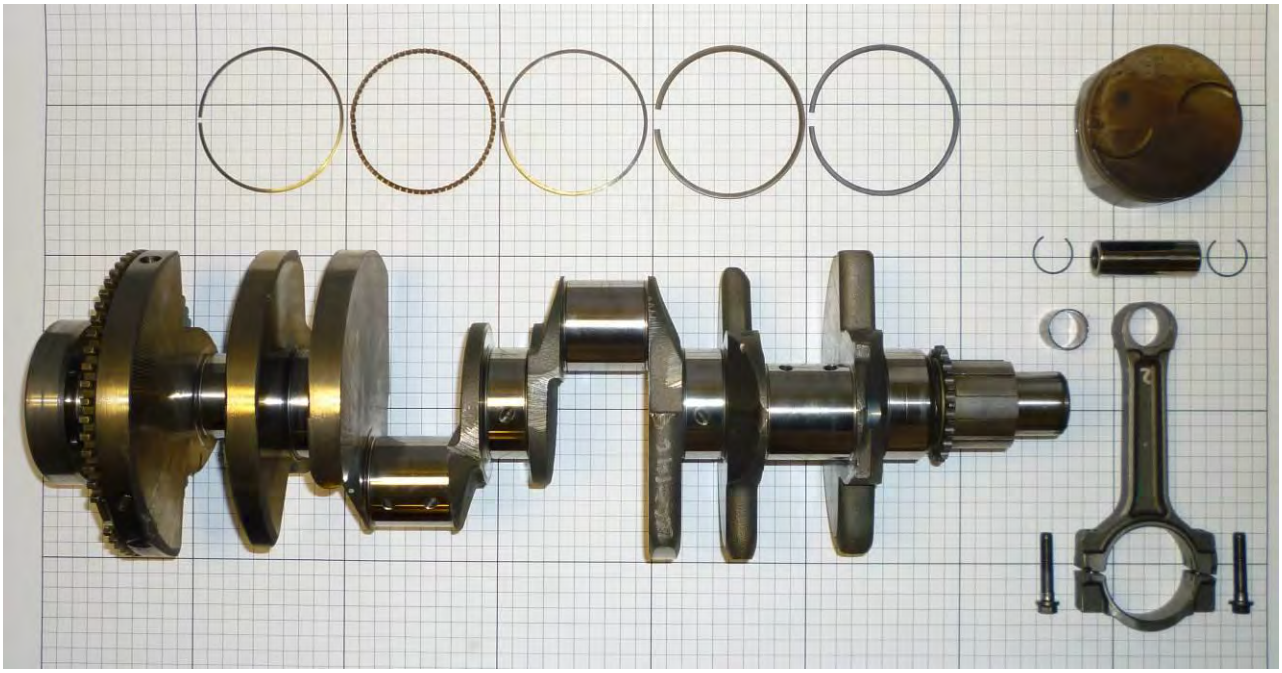

**Image 4.1-10: Key Components – Crank Drive**
*(Source: FEV, Inc.)*

### 4.1.2.3 Mass Reduction Industry Trends

In general, connecting rods are highly engineered and optimized. OEMs looking to reduce mass of the connecting rod are using a premium steel and optimizing geometry. Crack break forged steels such as C-70, C-70+, and 46MnVs4 provide a strength advantage and therefore a mass savings over a powder metal rod. They are also cost-competitive.

High-performance applications such as the Corvette, Porsche, and Acura NSX use titanium. Although titanium connecting rods (**Image 4.1-12**) have superior performance at high RPM, titanium's cost limits its use to high-performance applications. Titanium connecting rods increase cost by roughly $50.00 per kg of mass saved.

Aluminum connecting rods (**Image 4.1-11**) are popular in the racing industry and can be purchased from a variety of manufactures. Although typically machined from billet, forged versions are also available. While lighter aluminum rods contribute to better engine acceleration, they have durability and packaging issues not suiting them for production use.

Aluminum metal matrix composites (MMCs) have proven themselves in the racing industry. Aluminum MMCs have found success in wrist pin, connecting rod and piston applications. The current cost of MMCs are cost prohibitive at roughly $60.00 per kg saved, limiting their use to performance-driven racing applications.

 

**Image 4.1-11: (Left) Aluminum Connecting Rod**
*(Source: www.extremepsi.com)*

**Image 4.1-12: (Right) Titanium Connecting Rod**
*(Source: http://www.citycratemotors.com)*

Crankshafts and pistons have fewer examples of lightweighting. Production pistons are already lightweight aluminum, and packaging constraints associated with crankshafts require the strength of steel and sufficient mass to counter the connecting rods.

#### 4.1.2.4 Summary of Mass Reduction Concepts Considered

**Table 4.1-8** lists the mass reduction ideas considered for the Crank Drive Subsystem.

**Table 4.1-8: Summary of Mass Reduction Concepts Considered for the Crank Drive Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Crankshaft | Hollow cast | 5% mass reduction | Oil porting challenge, increases main journal diameter |
| Crankshaft | Drilled rod mains | 2% mass reduction | Additional Operation, Oil porting challenge |
| Crankshaft | Drilled mains | 2% mass reduction | Additional Operation, Oil porting challenge |
| Crankshaft | Undercut counter weights | 5% mass reduction | Increases counterweight diameter, difficult to machine |
| Crankshaft | Cast to forged and downsized | 5% mass reduction | Forging cost premium |
| Crankshaft | Premium material | 10% mass reduction | Size is driven by mating components |
| Crankshaft Position Target | Thin stamp | 75% mass reduction | Effects crankshaft balance |
| Crankshaft Position Target | External crank target sensor | 75% mass reduction | Effects crankshaft balance |
| Flywheel | Add Lightening Holes | 5% mass reduction | Insufficient strength |
| Flywheel | Aluminum with bolted ring gear | 0% mass reduction | mass neutral |
| Flywheel | Mild Steel to AHSS | 15% mass reduction | Limitations due to formability/weldability |
| Connecting Rod | Con Rod Material & Geometry Optimization | 20% mass reduction | Crack forge steel offers strength and cost advantage |
| Connecting Rod | High copper alloy | 0% mass reduction | Mass neutral |
| Connecting Rods | Alloy Steel to Al/MMC | 45% mass reduction | Cost prohibitive |
| Connecting Rod | Titanium | 45% mass reduction | Cost prohibitive |
| Connecting Rod | Aluminum | 30% mass reduction | Durability concern - fatigue life |
| Piston | Aluminum to Aluminum-MMC | 25% mass reduction | Cost prohibitive |
| Piston | Weight Reduction Pockets | 25% mass reduction | Direct injection technology |
| Wrist Pin | Steel to Aluminum-MMC | 35% mass reduction | Cost prohibitive |
| Wrist Pin | Steel to tool steel | 0% mass reduction | Material already optimized |
| Wrist Pin | trapezoidal cross section | 20% mass reduction | Added manufacturing complexity |

Concepts for lightweighting the crankshaft center around removing non-stressed areas such as hollowing the mains and optimizing counter weight geometry. Changing the forming process from cast to forge was reviewed, but detailed design work would be required to quantify mass savings. Opportunity to leverage the improved mechanical properties of forged steel is limited by cylinder block driven geometry. Driven by performance, a number of lightweighting options have been successfully implemented for connecting rods, wristpins, and pistons, however these solutions are cost prohibitive for standard performance engine systems.

Other ideas considered included crankshaft position target and flexplate. The LC9 crankshaft position target appears to be integral to crankshaft balancing and, therefore, was not lightweighted. Aluminum flexplates are available for aftermarket applications, but the gear requires steel for strength. Also, the fasteners used to join the aluminum hub and gear offset mass savings and increase cost.

#### 4.1.2.5 Selection of Mass Reduction Ideas

**Table 4.1-9** lists mass reduction ideas applied to Crank Drive Subsystem.

**Table 4.1-9: Mass Reduction Ideas Selected for Crank Drive Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **03** | **00** | **Crank Drive Subsystem** | |
| 01 | 03 | 01 | Crankshaft | Hollow-Cast |
| 01 | 03 | 02 | Flywheel | N/A |
| 01 | 03 | 03 | Connect Rods (Assemblies: Connecting Rod, Connecting Rod Cap) | Geometry optimization using C-70 |
| 01 | 03 | 04 | Pistons (Assemblies, Including Pistons, Ring Packs, Piston Pins, Circlips) | Wristpin trapezoidal cross section |
| 01 | 03 | 05 | Drive for Accessory Drives (Down force, Flywheel side) | N/A |
| 01 | 03 | 10 | Drive for Timing Drive (Down force, Flywheel side) | N/A |
| 01 | 03 | 15 | Adaptors | N/A |
| 01 | 03 | 99 | Misc. | N/A |
| | | | | |

Silverado features a solid cast crankshaft (**Image 4.1-13**). Cored crankshafts (**Image 4.1-14**) save mass by removing non-stressed mass from the main journals. Using a casting core, geometry can be optimized to maintain strength while providing material to house required oil porting. The use of cores eliminates the need for additional machining. Production applications include BMW's 4.4L V8 (**Image 4.1-15**) and Infinity 4.5L V8.

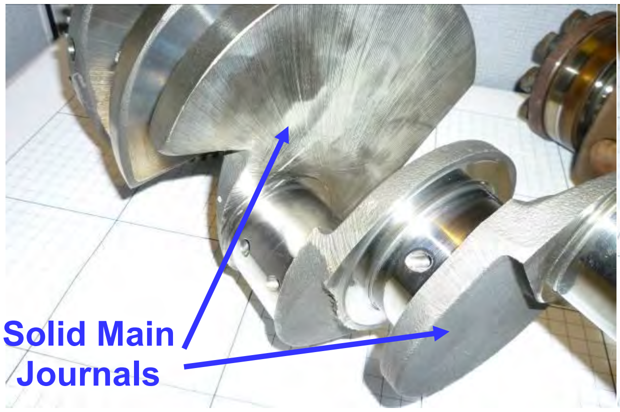



**Image 4.1-13: (Left) Solid Cast Crankshaft (Silverado)**
*(Source: FEV, Inc.)*

**Image 4.1-14: (Right) Cored Crankshaft (BMW)**
*(Source: FEV, Inc.)*

**Image 4.1-15: BMW 4.4L V8**
*(Source: eurochopshop.com. photo)*

Forged connecting rods have a strength advantage over powder metal. To quantify the mass savings potential of moving to a forged rod, FEV began by estimating the peak combustion pressure (70 bar) based on similar engines and applied a 1.1 safety factor to calculate the peak compressive force. The piston mass and peak RPM were used to calculate peak tension force occurring during the intake stroke, again using 1.1 SF. The

LC9 PM rod (**Image 4.1-16**) and a lightweight C-70 rod (**Image 4.1-17**) were modeled in CAD.


**Image 4.1-16: (Left) Vortech PM Rod**
*(Source: FEV, Inc.)*

**Image 4.1-17: (Right) FEV C-70 Rod**
*(Source: FEV, Inc.)*

Loads were applied to determine minimum and maximum principle stresses (**Image 4.1-18**). Based on these stresses fatigue life was calculated for both rods. Fatigue results for the C-70 rod initially did not meet minimum life and geometry required numerous iterations to achieve the final result of 23% mass savings or 1.07 kg per vehicle. Fatigue life of the optimized C-70 rod exceeds that of the Silverado PM Rod as modeled by FEV. While the lightweighted connecting rod impacts the overall vehicle weight, the most significant benefit is reduced friction and improved mechanical efficiency[29].

29 media.gm.com/media/us/en/gm/press_kits.detail.html/content/Pages/news/us/en/2012/May/0510_ats.html

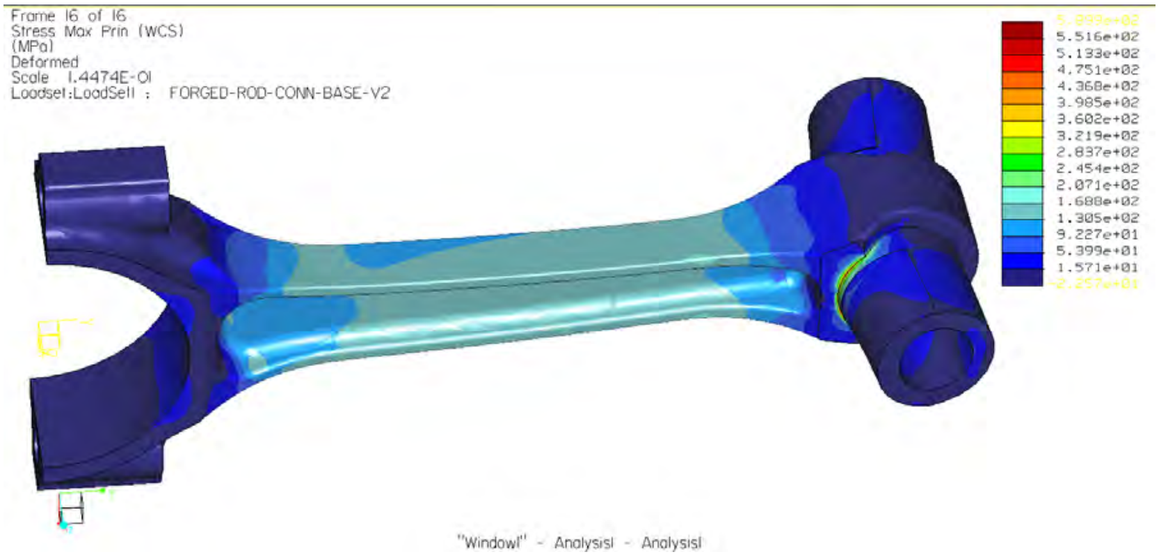


**Image 4.1-18: FEV C-70 Rod Principle Stress Analysis**
*(Source: FEV, Inc.)*

The piston pin found on Silverado is a forged tube of equal wall thickness across its length (**Image 4.1-19**) and represents a standard design for piston pins. Tapering the pin cross section (**Image 4.1-20**) by increasing the inner diameter toward the pin ends reduces mass while maintaining strength requirements. The taper feature can be integrated into the cold forming operation to minimize costs. Piston pin tapering saves 23% mass.

**Image 4.1-19: (Left) Silverado Piston Pin**
*(Source: FEV, Inc.)*

**Image 4.1-20: (Right) Tapered Piston Pin**
*(Source: http://77e21.info/strokerbuildbottomend.htm.)*

#### 4.1.2.6 Calculated Mass Reduction and Cost Impact Results

As shown in **Table 4.1-10**, mass reductions for the Crank Drive Subsystem save $1.24 per kg. The cost savings for this subsystem is a result of processing savings of a hot forged connecting rod as compared to a powder metal connecting rod. Cost increases were estimated for the crankshaft and piston pin.

**Table 4.1-10: Mass Reduction and Cost Impact for Crank Drive Subsystem**

*(See Appendix for Additional Cost Detail)*

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 01 | 03 | 00 | Crank Drive Subsystem | | | | | | |
| 01 | 03 | 01 | Crankshaft | C | 1.032 | -$2.29 | -$2.22 | 4.30% | 0.04% |
| 01 | 03 | 02 | Flywheel | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 03 | 03 | Connect Rods (Assemblies: Connecting Rod, Connecting Rod Cap) | A | 1.072 | $6.34 | $5.92 | 19.82% | 0.04% |
| 01 | 03 | 04 | Pistons (Assemblies, Including Pistons, Ring Packs, Piston Pins, Circlips) | D | 0.272 | -$1.10 | -$4.05 | 5.44% | 0.01% |
| 01 | 03 | 65 | Drive for Accessory Drives (Down force, Flywheel side) | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 03 | 66 | Drive for Timing Drive (Down force, Flywheel side) | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 03 | 67 | Adaptors | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 03 | 99 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | A | 2.376 (Decrease) | 2.952 (Decrease) | $1.24 (Decrease) | 6.42% | 0.10% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.1.3 Cylinder Block Subsystem

#### 4.1.3.1 Subsystem Content Overview

As seen in **Table 4.1-11**, the cylinder block is the most massive Engine Subsystem, making up 25% of the total Engine System mass.

**Table 4.1-11: Mass Breakdown by Sub-subsystem for Cylinder Block Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 05 | 00 | Cylinder Block Subsystem | |
| 01 | 05 | 01 | Cylinder Block | 47.150 |
| 01 | 05 | 02 | Crankshaft Bearing Caps | 7.782 |
| 01 | 05 | 03 | Bedplates | 0.000 |
| 01 | 05 | 04 | Piston Cooling | 0.000 |
| 01 | 05 | 65 | Crankcase Adaptor | 0.000 |
| 01 | 05 | 66 | Water Jacket | 0.000 |
| 01 | 05 | 67 | Clinder Barrel | 0.000 |
| 01 | 05 | 99 | Misc. | 4.932 |
| | | | | |
| | | | Total Subsystem Mass = | 59.864 |
| | | | Total System Mass = | 239.945 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 24.95% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 2.44% |

#### 4.1.3.2 Chevrolet Silverado Baseline Subsystem Technology

Silverado's 5.3L features lightweight aluminum construction (**Image 4.1-21**). The sand cast aluminum cylinder block is a deep skirt style with 6-bolt mains and powder metal main caps. The dry sleeve, closed deck design consists of cast iron liners over-molded into the cylinder block. Other components included in this subsystem are front cover, rear cover, and cylinder deactivation assembly – all diecast aluminum. Thick sections, 6-bolt mains, and closed deck features make the generation IV block an extremely durable design.

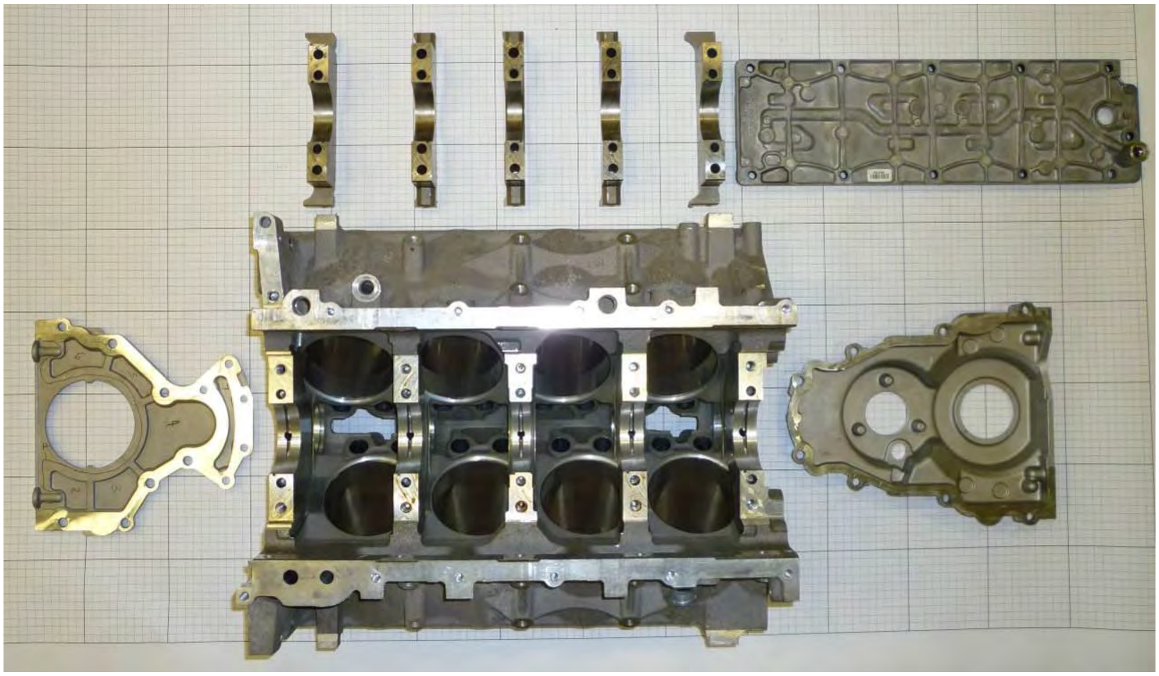

**Image 4.1-21: Key Components – Cylinder Block Subsystem**
*(Source: FEV, Inc.)*

#### 4.1.3.3 Mass Reduction Industry Trends

Grey cast iron is still a popular choice for engine blocks. Among the advantages are strength, wear performance, corrosion resistance, castability, NVH, and cost. Compacted graphite iron (CGI) is increasing in popularity for its improved strength over grey cast iron, permitting thinner cross sections and weight reductions over conventional grey cast.[30] CGI is mostly used in European diesel engine applications. Over the past decade, the weight advantage of aluminum has fostered its growth as a material choice for engine blocks and now makes up 60% of engine blocks in production. Under consumer pressure for better fuel economy automakers are now turning their attention to the even lighter magnesium alloys for engine block applications.

Volkswagen has used magnesium cylinders in its four-cylinder air-cooled boxer engine in the Beatle and other vehicles for decades. BMW has taken the lead in magnesium alloy engine block applications. BMW's Z4 Roadster debuted in 2004 as the lightest 3.0 L inline six-cylinder gas engine in the world, made possible by the composite magnesium-aluminum alloy engine. The engines success lead to its implementation in subsequent BMW models exceeding over 300,000 units in 2006[31].

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30 http://claymore.engineer.gvsu.edu/~nguyenn/egr250/automotive%20engine%20bl

31 http://www.intlmag.org/files/mg001.pdf

In 2010, a joint effort among GM, Ford, and Chrysler concluded through extensive testing magnesium was a feasible engine block material as tested on the Ford Duratec® 2.5L V6. Changes for successful implementation include ethylene glycol coolant with magnesium protective additives and a new head gasket design to accommodate the aluminum head to magnesium block interface. Iron bulkheads were also required for added strength and further bulk head development is required to prevent failures. The engine block mass was reduced by 25% without any significant compromises to performance.[32] Increasing peak combustion pressures associated with the recent turbo downsizing trend are driving a need for stronger cylinder block materials and a potential turn away from magnesium development.

#### 4.1.3.4 Summary of Mass Reduction Concepts Considered

**Table 4.1-12** lists the mass reduction ideas considered for the Cylinder Block Subsystem.

**Table 4.1-12: Summary of Mass Reduction Concepts Considered for the Cylinder Block Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| | | | |
| Rear Main Seal Retainer | Aluminum to Magnesium | 30% mass reduction | Cost increase |
| Rear Main Seal Retainer | Aluminum to Plastic | 40% mass reduction | Structural Loss |
| Cylinder Liner | Plasma Cylinder Liner | 55% mass reduction | Improved heat transfer |
| Cylinder Liner | Dual Material (Federal-Mogul) | 0% mass reduction | Enables engine downsizing by strengthening cast liner bond |
| Core Plugs | Steel to Aluminum | 50% mass reduction | Limited mass savings impact |
| Cylinder Block | Reduce size of cyl deactivation bosses | 2% mass reduction | Requires two piece core, Cost Prohibitive |
| Cylinder Block | PM MMC structural insert | 10% mass reduction | Cost prohibitive |
| Main Bearing Caps | Geometry optimization | 0% mass reduction | All area is functional |
| Main Bearing Caps | Cast Iron to PM MMC | 45% mass reduction | Cost prohibitive |
| Cylinder Deactivation Assembly | Upper Plate - Aluminum to Magnesium | 30% mass reduction | Coated fasteners required |
| Cylinder Deactivation Assembly | Integrate coil mounts into Cylinder Block | 20% mass reduction | CAE model required for evaluation |
| Cylinder Deactivation Assembly | Upper Plate - Aluminum to plastic | 50% mass reduction | Strength concern |

32 www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2010/wednesday/presentations/deer10_powell.pdf

Magnesium and plastic were considered for lightweighting the rear main seal retainer. Plastic has a mass savings and cost advantage over magnesium but less durable.

A dual material cylinder liner offered by Federal Mogul increases the bond between cast iron cylinder liners and the aluminum cylinder block, reducing bore distortion and permitting higher combustion pressures. This technology, however, does not exhibit opportunity for the naturally aspirated Silverado engine.

Powder metal matrix composite (MMC) was considered for the main bearing caps and would save significant mass. Aluminum MMCs have also been used as structural reinforcing members of racing engine blocks and could potentially save mass. Aluminum MMCs at this point are cost-limited to racing applications. The relatively inexpensive cost of the raw materials may make aluminum MMCs a key consideration in future lightweighting.

Mass reduction opportunities for cylinder deactivation include material replacements for the aluminum mounting plate, direct mounting of the control coils to the cylinder block and optimizing the block port bosses. Due to hydraulic pressures required to drive the valvetrain, plastic was eliminated from consideration as a mounting plate material. Direct mounting of the control coils has potential for mass reduction but requires CAE modeling for evaluation. The wall thickness of the cylinder deactivation bosses connecting the deactivation assembly to the lifters appears to have opportunity for material removal (**Image 4.1-22**). Reducing boss thickness either requires a new sealing design or stepping out the diameter to maintain the sealing surface area.

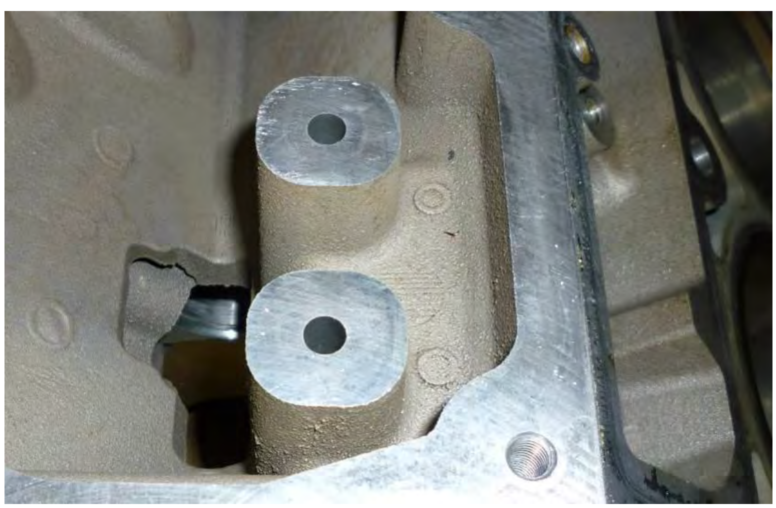

**Image 4.1-22: Cylinder Deactivation Bosses**
*(Source: FEV, Inc.)*

#### 4.1.3.5 Selection of Mass Reduction Ideas

**Table 4.1-13** outlines the ideas selected to lightweight the Cylinder Block Subsystem.

**Table 4.1-13: Mass Reduction Ideas Selected for Cylinder Block Subsystem Analysis**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **05** | **00** | **Cylinder Block Subsystem** | |
| 01 | 05 | 01 | Cylinder Block | Rear Main Seal Retainer - Aluminum to Plastic<br>Cylinder Liner - cast steel to plasma coated |
| 01 | 05 | 02 | Crankshaft Bearing Caps | N/A |
| 01 | 05 | 03 | Bedplates | N/A |
| 01 | 05 | 04 | Piston Cooling | N/A |
| 01 | 05 | 65 | Crankcase Adaptor | N/A |
| 01 | 05 | 66 | Water Jacket | N/A |
| 01 | 05 | 67 | Cylinder Barrel | N/A |
| 01 | 05 | 99 | Misc. | Cylinder Deactivation Plate - Al to Mg |
| | | | | |

Heat stabilized PA4T-GF30 was selected to replace aluminum as a base material for the rear main seal housing (**Image 4.1-23**). This blend of polymer performs well under heat with 0.075mm of variation in the flow direction and 0.15mm of variation in the cross flow direction. Included in the cost evaluation are fastener support inserts, threaded inserts, and a main seal insert. A similar plastic application is the timing cover pictured in **Image 4.1-24**.


**Image 4.1-23: (Left) Silverado Main Seal Housing**
*(Source: FEV, Inc.)*

**Image 4.1-24: (Right) Plastic Timing Cover**
*(http://www.marinerecycling.com/parting_used_outboards.html)*

In order to stiffen the plastic version of the aluminum Silverado housing, 20% part volume was added resulting in an overall mass savings of 38%.

The Silverado Generation IV engine block uses standard cast iron cylinder liners. These liners are inserted into the casting cavity prior to filling. Following casting, the liners are machined to finish the cylinder bore. Plasma Transfer Wire Arc (PTWA) is a new method of forming an iron surface for the cylinder wall (**Image 4.1-25**). The alternative process began development by Ford in the early 1990s and was first implemented on the 2008 Nissan GT-R and the 2011 Shelby Mustang GT500. With PTWA, the aluminum engine block is cast without liners and the aluminum bore is pre-machined to near net size. The bore is then cleaned and fluxed, followed by a bonding coat. Low carbon steel wire is continuously fed into the nozzle apparatus and deposited on the cylinder wall. After matching the remaining plasma coating is .070-.170 mm in thickness. This is roughly 10% of the cast liner thickness found on Silverado's 5.3L. This ultra-thin surface improves heat transfer (**Image 4.1-26**) between the combustion process and the aluminum block.[33] Although Ford has patented its PTWA process, plasma can be used to apply cylinder coatings in a variety of ways: BMW's new N20 engine block uses two iron wires in a similar process. Volkswagen has a cylinder coating process in which steel and molybdenum powder is applied by a plasma jet. Production applications included Volkswagen's Touareg, Lupo, and Van T5. High-Velocity Oxy-Fuel (HVOF) has also been used for the cylinder friction surfaces. In addition to weight savings, plasma liners offer improved overall performance and durability, along with functional benefits of improved heat transfer and reduced friction between piston rings and cylinder bores.[34]

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33 http://www.me.berkeley.edu/~mford/Ford_Fisher_PTWA.pdf

34 http://svtusa.com/2010/02/hello-world/

 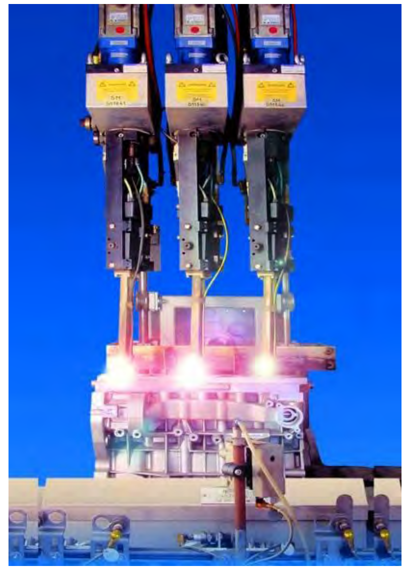

**Image 4.1-25: (Left) [Base Technology] Cast Iron Cylinder Liners**
*(Source: http://www.anandenterprise.com/innovation.html)*

**Image 4.1-26: (Right) [New Technology] Plasma Transfer Wire Arc (PTWA)**
*(Source: http://www.greencarcongress.com/2009/05/ptwa*-20090529.html)

Dimensions for Silverado's cast cylinder liner were estimated at an average thickness of 1.7 mm and 526 grams per liner. A plasma liner mass estimate was developed using 0.15 mm thickness resulting in a mass savings of 2.36 kg for the engine. Additional cast aluminum mass and cost required for PTWA was included.

The cylinder deactivation plate (**Image 4.1-27**) serves as a mounting location for the control solenoids and houses oil porting to the cylinder block. This plate, originally made from diecast aluminum, was changed to magnesium. 10% volume was added to increase strength in critical areas. Based on valve actuation forces magnesium's strength should be sufficient for the application.

**Image 4.1-27: Cylinder Deactivation Plate**
*(Source: FEV, Inc.)*

### 4.1.3.6 Mass reduction and Cost Impact Results

As shown in **Table 4.1-14**, mass reductions for the Cylinder Block Subsystem save costs. Results for cylinder deactivation lightweighting are listed in the Miscellaneous Sub-subsystem.

**Table 4.1-14: Mass Reduction and Cost Impact for Cylinder Block Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 01 | 05 | 00 | Cylinder Block Subsystem | | | | | | |
| 01 | 05 | 01 | Cylinder Block | A | 2.934 | $2.78 | $0.95 | 6.22% | 0.12% |
| 01 | 05 | 02 | Crankshaft Bearing Caps | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 05 | 03 | Bedplates | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 05 | 04 | Piston Cooling | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 05 | 65 | Crankcase Adaptor | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 05 | 66 | Water Jacket | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 05 | 67 | Clinder Barrel | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 05 | 99 | Misc. | X | 0.364 | -$1.98 | -$5.45 | 7.38% | 0.01% |
| | | | | A | 3.298 (Decrease) | 0.797 (Decrease) | $0.24 (Decrease) | 5.51% | 0.13% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.1.4 Cylinder Head Subsystem

#### 4.1.4.1 Subsystem Content Overview

As seen in **Table 4.1-15**, the bare head makes up a majority of the subsystem mass. Included in the cylinder head mass is all pressed hardware including valve seats. Included in "Other Parts for Cylinder Head" are the head gaskets, locators, and head bolts.

**Table 4.1-15: Mass Breakdown by Sub-subsystem for Cylinder Head Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 01 | 06 | 00 | Cylinder Head Subsystem | |
| 01 | 06 | 01 | Cylinder Head | 18.644 |
| 01 | 06 | 02 | Valve, Guides, Valve Seats | 0.000 |
| 01 | 06 | 03 | Guides for Valvetrain | 0.624 |
| 01 | 06 | 06 | Camshaft Bearing Housing | 0.260 |
| 01 | 06 | 07 | Camshaft Speed Sensor | 0.028 |
| 01 | 06 | 08 | Camshaft Carrier | 0.000 |
| 01 | 06 | 09 | Other Parts for Cylinder Head | 2.576 |
| 01 | 06 | 20 | Cylinder Head Covers | 2.641 |
| 01 | 06 | 99 | Misc. | 0.129 |
| | | | | |
| | | | Total Subsystem Mass = | 24.902 |
| | | | Total System Mass = | 239.945 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 10.38% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.01% |

#### 4.1.4.2 Chevrolet Silverado Baseline Subsystem Technology

**Image 4.1-28** highlights the key Cylinder Head Subsystem components. Each Vortec aluminum cylinder head mounts to the block with 15 fasteners. Cylinder head geometry is optimized for manufacturability and packaging. Two valve per cylinder cam-in-block results in a simplified cylinder head. The Vortec is a wedge-type cylinder head, with spark plug entering from the side of the head.

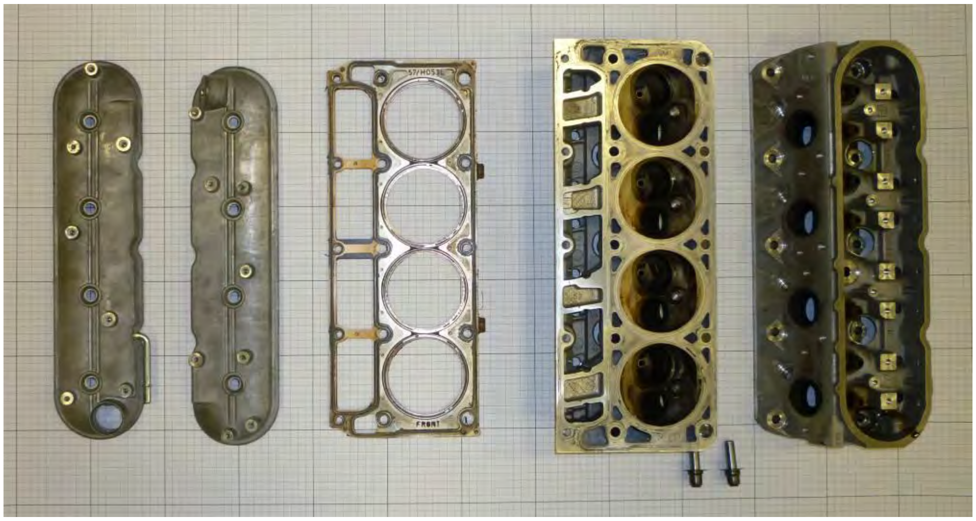

**Image 4.1-28: Key Components – Cylinder Head Subsystem**
*(Source: FEV, Inc.)*

### 4.1.4.3 Mass Reduction Industry Trends

Cylinder head industry trends for lightweighting have been limited to the use of aluminum. Magnesium alloy development for cylinder heads is ongoing and aims to resolve stiffness, creep, and corrosion issues. In 2008, the Changchun Institute of Applied Chemistry of CAS and FAW Group successfully developed a magnesium alloy cylinder head for heavy-duty trucks. Over 15,000 cylinder heads have been produced from magnesium alloy for heavy-duty trucks.[35] A popular choice for lightweight camshaft covers continues to be plastic as well as some use of magnesium.

### 4.1.4.4 Summary of Mass Reduction Concepts Considered

As a top subsystem mass contributor, the cylinder head was a focus for mass reduction. Magnesium as a material replacement for aluminum was researched. A production example of a magnesium cylinder head was difficult to find and no passenger car applications were identified. The valve cover, a commonly plastic component, was quickly identified as an opportunity. As another option for the valve cover, magnesium offers mass savings and good durability but at a price premium.

Lowering the cylinder head deck height and adding depth to the valve cover. This idea has potential to save mass but considering sophistication of cylinder head design this requires detailed design work to validate functionality.

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35 http://www.mubea.com/english/download/NW_engl.pdf

Scalloping or removing material between the spark plugs was investigated for mass removal but doing so interferes with the water jacket. Reducing valve spring free height and hence reducing cylinder head height was investigated with Mubea and determined unfeasible. **Table 4.1-16** summarizes ideas considered for the Cylinder Head Subsystem.

**Table 4.1-16: Summary of Mass Reduction Concepts Considered for the Cylinder Head Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Cylinder Head | Lower Cylinder Head upper deck and add material to valve cover | 3% mass reduction | Design work required to validate functionality |
| Cylinder Head | Scallop Cylinder Head between spark plugs | 0% mass reduction | interferes with water jacket |
| Cylinder Head | Material change from Aluminum to Magnesium | 25% mass reduction | No applicable examples |
| Cylinder Head | Reduce height through valve spring optimization | 7% mass reduction | Valve Spring is already optimized |
| Valve Covers | Aluminum to Plastic | 50% mass reduction | Sealing improvements required |
| Valve Covers | Aluminum to Magnesium | 30% mass reduction | Coated fasteners required |

#### 4.1.4.5 Selection of Mass Reduction Ideas

**Table 4.1-17** outlines the mass reduction ideas selected for the Cylinder Head Subsystem. Lightweight and cost-effective, plastic has been proved viable as a Cylinder Head Cover material.

**Table 4.1-17: Mass Reduction Ideas Selected for Cylinder Head Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **06** | **00** | **Cylinder Head Subsystem** | |
| 01 | 06 | 01 | Cylinder Head | N/A |
| 01 | 06 | 02 | Valve, Guides, Valve Seats | N/A |
| 01 | 06 | 03 | Guides for Valvetrain | N/A |
| 01 | 06 | 06 | Camshaft Bearing Housing | N/A |
| 01 | 06 | 07 | Camshaft Speed Sensor | N/A |
| 01 | 06 | 08 | Camshaft Carrier | N/A |
| 01 | 06 | 09 | Other Parts for Cylinder Head | N/A |
| 01 | 06 | 20 | Cylinder Head Covers | Cylinder Head Cover - Aluminum to Plastic |
| | | | | |

The aluminum valve cover was changed to plastic as a weight save, cost save, and performance benefit. Production examples include the Chrysler 4.7L V8 (**Image 4.1-30**) and the Ford Duratec 2.0L.


**Image 4.1-29: (Left) Silverado Valve Cover**
*(Source: FEV, Inc.)*

**Image 4.1-30: (Right) Chrysler 4.7L V8 Valve Cover**
*(Source: www.speautomotive.com)*

### 4.1.4.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.1-18** summarizes lightweight activities applied to Cylinder Head Subsystem. Plastic valve covers save over a kilogram of mass and are significantly less expensive than cast aluminum. Fastener isolators with compression limiters were included in the cost of the plastic covers. Implementing plastic in valve covers requires NVH considerations.

**Table 4.1-18: Mass Reduction and Cost Impact for Cylinder Head Subsystem**

*(See Appendix for Additional Cost Detail)*

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 01 | 06 | 00 | **Cylinder Head Subsystem** | | | | | | |
| 01 | 06 | 01 | Cylinder Head | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 06 | 02 | Valve, Guides, Valve Seats | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 06 | 03 | Guides for Valvetrain | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 06 | 06 | Camshaft Bearing Housing | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 06 | 07 | Camshaft Speed Sensor | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 06 | 08 | Camshaft Carrier | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 06 | 09 | Other Parts for Cylinder Head | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 06 | 20 | Cylinder Head Covers | A | 1.161 | $6.06 | $5.22 | 43.96% | 0.05% |
| 01 | 06 | 99 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | **A** | **1.161** (Decrease) | **6.058** (Decrease) | **$5.22** (Decrease) | **4.66%** | **0.05%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.1.5 Valvetrain Subsystem

### 4.1.5.1 Subsystem Content Overview

As seen in **Table 4.1-19**, the most significant subsystem mass contributors were the valve actuation elements followed by the camshaft. Weighing over 2 kg, the cam phaser has notable mass content.

**Table 4.1-19: Mass Breakdown by Sub-subsystem for Valvetrain Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 01 | 07 | 00 | **Valvetrain Subsystem** | |
| 01 | 07 | 01 | Inlet Valves | 0.688 |
| 01 | 07 | 02 | Outlet Valves | 0.776 |
| 01 | 07 | 03 | Valve Springs | 1.264 |
| 01 | 07 | 04 | Spring Retainers, Cotters, Spring Seats | 0.184 |
| 01 | 07 | 05 | Valve Actuation Elements: Rockers, Finger Followers, Hydraulic Lash Adjusters,... | 6.380 |
| 01 | 07 | 06 | Camshafts | 4.604 |
| 01 | 07 | 08 | Camshaft Phaser and/or Cam Sprockets | 2.362 |
| 01 | 07 | 99 | Misc. | 0.000 |
| | | | | |
| | | | **Total Subsystem Mass =** | **16.258** |
| | | | **Total System Mass =** | **239.945** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **6.78%** |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | **0.66%** |

#### 4.1.5.2 Chevrolet Silverado Baseline Subsystem Technology

The Silverado valvetrain assembly can be seen in **Image 4.1-31**. Baseline technology begins with a solenoid actuated hydraulic cam phaser. The cam phaser varies the intake and exhaust timing events making this a variable valve timing engine. The cam phaser consists of four main components; stator/drive gear, rotor, back plate and cover plate. The cover plate is cold formed steel while the remaining components are sintered iron. The camshaft timing target and phaser harness bracket are constructed of stamped steel.

GM's cam in block design utilizes hydraulic roller tappets to control valve lash. Half of the tappets have an additional hydraulic collapsing spring mechanism used for cylinder deactivation. The feature allows the valves to remain shut through the intake and exhaust cycles to save fuel under low-load conditions. Standard push rods drive steel rockers arms actuating the valves. The Silverado's valve springs are a beehive shape, tapered toward the top of the spring. This lightweight design reduces valve spring retainer diameter, thus saving mass. The engine valves are solid steel. The camshaft is core drilled to reduce mass.

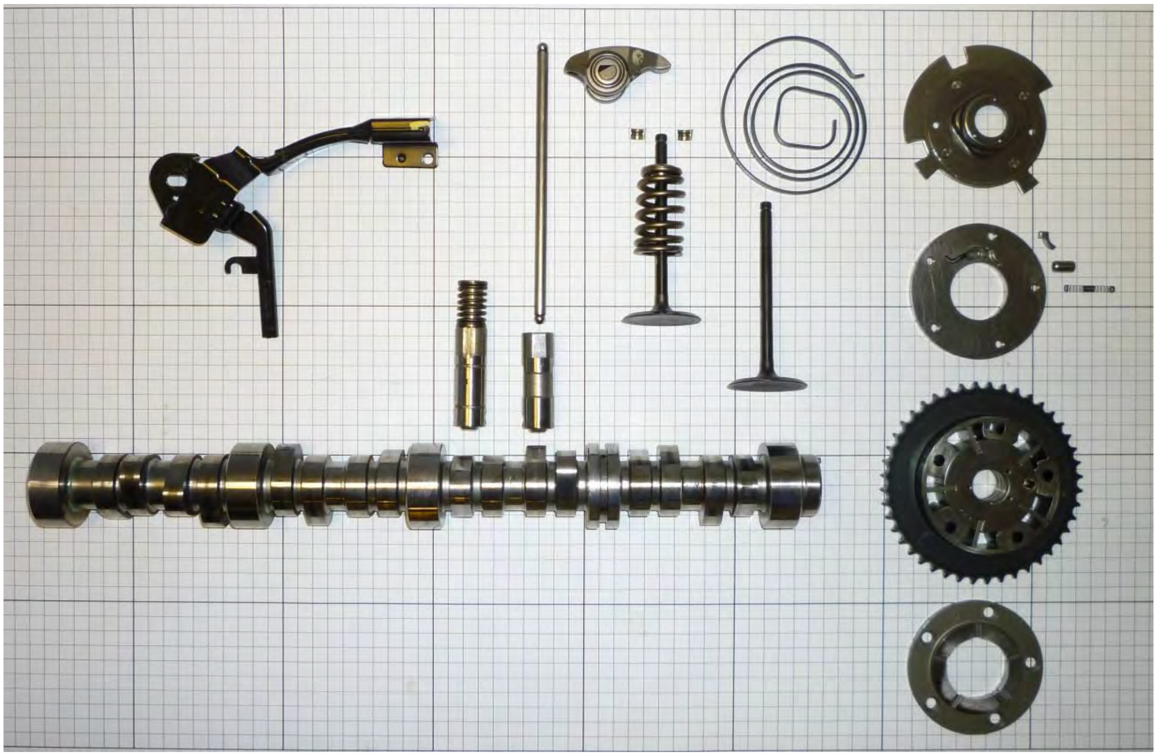

**Image 4.1-31: Valvetrain Assembly**
*(Source: FEV, Inc.)*

#### 4.1.5.3 Mass Reduction Industry Trends

Composite or tubular camshafts used in Europe are made from seamless tube. Cam lobes made from powder metal or forged steel are hydroformed in place. Composite camshafts offer weight savings of up to 50% over traditional solid cast.

Advances in valve spring technology have led to many new design options, including symmetrical, asymmetrical coiling, and tapered springs or beehive springs. All spring types can be made from wire with round or profiled cross sections. Advances in materials and processing techniques now permit lighter spring weights, smaller retaining diameters, and shorter free lengths.

Mubea, a leading supplier of valve springs offers improvements over traditional designs and manufacturing techniques.

Mubea offers ovate wire profiles (**Image 4.1-32**). As compared to conventional round, ovate wire reduces the solid height of the spring (**Image 4.1-33**). The installed height can be reduced proportionally. Mubea's spring also undergoes a special hardening process after coiling. This optimizes the residual stress profile, resulting in the best possible material properties and enabling a reduced wire diameter. The smaller wire diameter reduces the solid height and resultant installed height. The shorter spring offers a packaging advantage for cylinder head designers that can lead to reductions in cylinder head size and valve length. Further refinements include a beehive style or tapered spring (**Image 4.1-33**) that can reduce the valve keeper size. Lighter valve hardware mean reduced inertia, less friction, and improved efficiency.

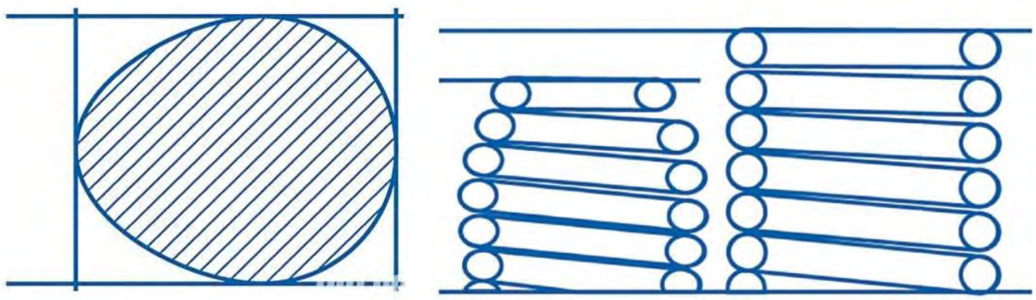

**Image 4.1-32: (Left) Ovate Wire Profile**
*(Source: HotRod.com)*

**Image 4.1-33: (Right) Spring Height, Ovate vs. Standard**
*(Source: HotRod.com)*

### 4.1.5.4 Summary of Mass Reduction Concepts Considered

As seen in **Table 4.1-20**, a variety of components were considered for mass reduction.

**Table 4.1-20: Summary of Mass Reduction Concepts Considered for Valvetrain Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Exhaust Valve | Solid to Sodium Filled | 20% mass reduction | Cost prohibitive / performance advantage |
| Exhaust Valve | Steel to Titanium | 45% mass reduction | Cost prohibitive / performance advantage |
| Exhaust Valve | Solid to Sheet Steel | 50% mass reduction | Cost prohibitive / performance advantage |
| Exhaust Valve | Hollow Head Valve (MHI) | 15% mass reduction | Cost prohibitive / performance advantage |
| Exhaust Valve | Steel to Ceramic (Si3N4) | 30% mass reduction | No applicable examples for petrol engines |
| Exhaust Valve | Steel to Carbon Reinforced Polymer | 80% mass reduction | Cost prohibitive, durability issues |
| Valve Spring | Reduce wire diameter | 10% mass reduction | durability issues |
| Valve Spring | Reduce coil count | 10% mass reduction | durability issues |
| Rocker Carrier Base | Aluminum to Magnesium | 30% mass reduction | Incompatible with Steel rocker mount, limited opportunity |
| Rocker Carrier Base | Integrate into Cylinder Head | 50% mass reduction | Manufacturability concern, limited opportunity |
| Rocker Arm | Steel to Aluminum | 50% mass reduction | Packaging issue |
| Valve Spring Retainer | Steel to Titanium | 45% mass reduction | Cost prohibitive / performance advantage |
| Push Rod | Steel to AHSS | 10% mass reduction | Limited opportunity |
| Camshaft | Solid Cast to Tubular Composite | 20% mass reduction | Cost Prohibitive |
| Camshaft | Solid cast to hollow cast | 20% mass reduction | Reduced strength |
| Cam Retaining Plate | Steel to Aluminum | 45% mass reduction | Bearing insert required |
| Cam Sensor Target | solid steel to plastic with metal insert | 50% mass reduction | Limited opportunity, joining issue |
| Cam Phaser | Cover & Back Plate - Iron to Aluminum | 15% mass reduction | Aluminum wear surfaces Insufficient Strength |
| Cam Phaser | Stator, Rotor, & Cover Plate - Iron to Aluminum | 30% mass reduction | insufficient rotor strength |
| Cam Phaser | Stator & Cover integrated into Plastic | 60% mass reduction | limited to belt drive |
| Cam Phaser | Gear material from Steel to Titanium | 15% mass reduction | Cost prohibitive |
| Cam Phaser | Lightening windows around Stator bolts | 5% mass reduction | Limited opportunity |
| Cam Phaser Harness Bracket | Steel to Plastic | 75% mass reduction | Component reduction |

Due to the relationship between valve train mass and performance, much work has been done in the area of valvetrain lightweighting. Although viable for high-output, high-revving engines, these performance-driven solutions were not found to be economical from a standpoint of vehicle mass reduction.

A variety of lightweight valve materials were considered as replacements for Silverado's steel valves. Sodium engine valves have a cavity created by a hollow stem and are partially filled with sodium. Back-and-forth sloshing, driven by the action of the valve, transfers heat from the head of the valve through to the stem, evening the valve temperatures. A sodium-filled Corvette engine valve was analyzed as the subject of this study (**Image 4.1-34**). Although lighter, the engine was determined to be cost-prohibitive for vehicle lightweighting despite drilling, reaming, filling, and welding of hollow valves.

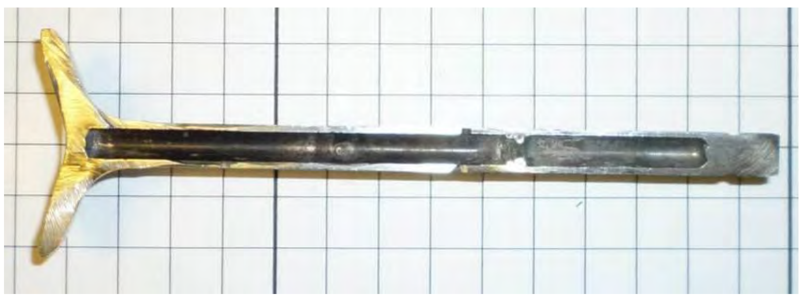

**Image 4.1-34: Hollow Stem Engine Valve - Corvette**
*(Source: FEV, Inc.)*

Titanium can be found within various valvetrain components, including valves. Although titanium is nearly half the density of steel with similar strength, its high cost limits use to high performance applications regardless of the engine component for which it is being considered. Popular applications include valves and valve spring retainers.

Mahle has developed a new lightweight engine valve with a welded structure made from cold formed steel sheet parts (**Image 4.1-35).** The precision laser-welded joint and cold-formed features require no additional processing: only the functional areas are still ground. Sodium can be introduced into the hollow cavity of the exhaust valves, reducing valve temperatures. Weight reductions of up to 50% are possible over conventional solid stem valves. Lighter valves enable lighter cam lobes, cam followers, tappets and valve springs.[36] Silverado valve geometry in its current design does not lend itself to sheet valve technology. A complete system redesign would be required to evaluate if this technology could work on Silverado and therefor this idea was not selected.

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36 http://www.foundryworld.com/english/news/view.asp?bid=106&id=264

**Image 4.1-35: Mahle Sheet Steel Valve**
*(Source: http://www.tokyo-motorshow.com)*

The base valve spring (**Image 4.1-36**) found on the Silverado has lightweight beehive geometry. Mubea, supplier of the valve spring and a leader in valve spring technology, reviewed the spring and indicated it is the lightest configuration available at this time.

**Image 4.1-36: [Base Technology] Valve Spring**
*(Source: FEV, Inc.)*

Rocker arms, traditionally made from steel, can be made from aluminum (

**Image** 4.1-37). Production examples include the Nissan Frontier and Isuzu Trooper. Arm ends require wear pads and all designs reviewed were continuous shaft mounted potentially creating packaging issues and cylinder head redesign with unknown mass impact. For this reason aluminum rocker arms were not implemented for Silverado mass savings.


**Image 4.1-37: Aluminum Rocker Arm**
*(Source: www.autohausaz.com)*

The cam phaser assembly, made up of many subcomponents, can be manufactured from powder metal aluminum rather than sintered iron (**Image 4.1-38**). SHW Automotive, a 2010 European Powder Metallurgy Association award winner for excellence in powder metal, offers this technology in large-scale production (700,000 units per year). In this application mass savings is complimented by a performance advantage of reducing valvetrain inertia.[37] In addition to aluminum, Hilite International has developed a plastic stator with integrated lid (**Image 4.1-39**). Initial testing of the concept has indicated promising durability. Plastic offers further mass savings and reduced costs. Due to the Silverado's valvetrain loads, aluminum and plastic were not selected for stator, rotor, or gear.

37 http://svtusa.com/2010/02/hello-world/

**Image 4.1-38: Aluminum Phaser Sprocket and Rotor**
*(Source: www.ipmd.net)*

**Image 4.1-39: Plastic Stator**
*(Source: www.hilite.com)*

Mubea develops lightweight vehicle technology and supplies composite camshafts to the European passenger car market (**Image 4.1-40**). Mubea's process uses internal high-pressure fluid to expand the camshaft tube inside servo positioned camshaft lobes. This assembly process opens the range of materials that can be considered for lobe design and concentrates the material to the critical cam lobe region.[38] GM's cam-in-block design requires that bearing diameters exceed lobe diameters. In addition, with a single cam servicing both intake and exhaust, loads are higher. Considering other alternatives,

38 http://www.foundryworld.com/english/news/view.asp?bid=106&id=264

hydroforming was not selected as the optimum manufacturing method for the Silverado application.

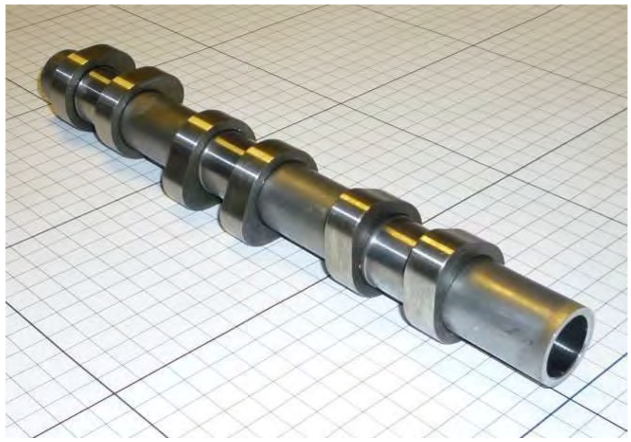
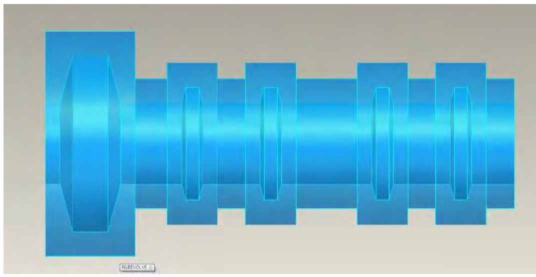


**Image 4.1-40: Hydroformed Camshaft**
*(Source: FEV, Inc.)*

Hollow cast camshafts are lightweighting technology that can be found in GM's Ecotec line-up. As part of a previous study, a 1.4L camshaft was purchased and sectioned (**Image 4.1-41**). Analysis found that the cored cavity saved 21% mass over the same camshaft cast from solid.

**Image 4.1-41: Hollow Cast Camshaft – 1.4L Ecotec**
*(Source: FEV, Inc.)*

Quantifying hollow cast mass on Silverado's camshaft started by modeling the camshaft in CAD (**Image 4.1-42**). Using the Ecotec wall thickness (6 mm) and profiling outer geometry, the core cavity was created. Based on this analysis, a hollow cast camshaft saves 20% mass over the base core drilled camshaft (**Image 4.1-43**). Unfortunately, a hollow cast camshaft does not offer the strength required for this V8 application.



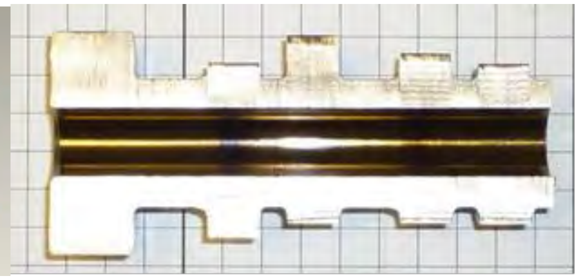


**Image 4.1-42: (Left): 5.3L Hollow Cast Concept CAD**
*(Source: FEV, Inc.)*

**Image 4.1-43: (Right): 5.3L Camshaft - Sectioned**
*(Source: FEV, Inc.)*

#### 4.1.5.5 Selection of Mass Reduction Ideas

**Table 4.1-21** lists the ideas selected for lightweighting the Silverado valvetrain. Due to the high costs of lightweighting valvetrain technologies, viable lightweighting opportunities were limited to the Camshaft Retaining Plate and Phaser Harness Bracket.

**Table 4.1-21: Mass Reduction Ideas Selected for Valvetrain Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **07** | **00** | **Valvetrain Subsystem** | |
| 01 | 07 | 01 | Inlet Valves | N/A |
| 01 | 07 | 02 | Outlet Valves | N/A |
| 01 | 07 | 03 | Valve Springs | N/A |
| 01 | 07 | 04 | Spring Retainers, Cotters, Spring Seats | N/A |
| 01 | 07 | 05 | Valve Actuation Elements: Rockers, Finger Followers, Hydraulic Lash Adjusters,… | N/A |
| 01 | 07 | 06 | Camshafts | Camshaft Retaining Plate - Steel to Al |
| 01 | 07 | 08 | Camshaft Phaser and/or Cam Sprockets | Cam Phaser Harness Bracket - Steel to Plastic |
| 01 | 07 | 99 | Misc. | N/A |
| | | | | |

The cam phaser wiring bracket is a stamped steel assembly (**Image 4.1-44**), but could be made from plastic to save mass. Metal to plastic conversion in this application saves 107 grams.

**Image 4.1-44: Wiring Bracket – Phaser**
*(Source: FEV, Inc.)*

The camshaft retaining plate (**Image 4.1-44**) was lightweighted by replacing the steel component with aluminum. The aluminum part would be designed with a steel insert pressed in to create a bearing surface for camshaft thrust.

**Image 4.1-45: Camshaft Retaining Plate – Phaser**
*(Source: FEV, Inc.)*

#### 4.1.5.6 Calculated Mass reduction and Cost Impact Results

As seen in **Table 4.1-22**, hollow cast camshaft saves nearly a kilogram. Moving from solid steel to cored cast iron reduces cost. Replacing steel with aluminum in the cam phaser covers increases cost. Overall, lightweighting of the Valvetrain Subsystem resulted in a moderate cost increase.

**Table 4.1-22: Mass Reduction and Cost Impact for Valvetrain Subsystem**
*(See Appendix for Additional Cost Detail)*

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| **01** | **07** | **00** | **Valvetain Subsystem** | | | | | | |
| 01 | 07 | 01 | Inlet Valves | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 07 | 02 | Outlet Valves | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 07 | 03 | Valve Springs | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 07 | 04 | Spring Retainers, Cotters, Spring Seats | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 07 | 05 | Valve Actuation Elements: Rockers, Finger Followers, Hydraulic Lash Adjusters,… | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 07 | 06 | Camshafts | B | 0.085 | -$0.03 | -$0.39 | 1.85% | 0.00% |
| 01 | 07 | 08 | Camshaft Phaser and/or Cam Sprockets | A | 0.107 | $0.08 | $0.78 | 4.51% | 0.00% |
| 01 | 07 | 99 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | **A** | **0.192** (Decrease) | **0.050** (Decrease) | **$0.26** (Decrease) | **1.18%** | **0.01%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.1.6 Timing Drive Subsystem

#### 4.1.6.1 Subsystem Content Overview

As seen in the following **Table 4.1-23**, the most significant mass contributors to the Timing Drive Subsystem are the covers and the chains. The driven timing sprocket was integrated into the cam phaser and the driving timing sprocket is included in the crankshaft mass, therefore no mass is reported for the Timing Wheels (Sprockets) Sub-subsystem. The guide and tensioner are one assembly, so mass was binned to the Guides Sub-subsystem.

**Table 4.1-23: Mass Breakdown by Sub-subsystem for Timing Drive Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 08 | 00 | **Timing Drive Subsystem** | |
| 01 | 08 | 01 | Timing Wheels (Sprockets) | 0.000 |
| 01 | 08 | 02 | Tensioners | 0.000 |
| 01 | 08 | 03 | Guides | 0.199 |
| 01 | 08 | 05 | Belts, Chains | 0.251 |
| 01 | 08 | 06 | Covers | 1.300 |
| 01 | 08 | 99 | Misc. | 0.000 |
| | | | | |
| | | | **Total Subsystem Mass =** | **1.750** |
| | | | **Total System Mass =** | **239.945** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **0.73%** |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | **0.07%** |

#### 4.1.6.2 Chevrolet Silverado Baseline Subsystem Technology

**Image 4.1-46** shows the Silverado timing drive with the oil pump assembled. The single cam-in-block design simplifies the Timing Drive System. The system starts with a timing drive gear pressed onto the crankshaft. This gear also features a splined hub driving the oil pump. Rotation is translated through a single roller chain driving the cam phaser. The timing chain tensioner has a stamped steel frame with plastic wear surfaces. A strip of spring steel creates the tensioning mechanism in this short drive system.

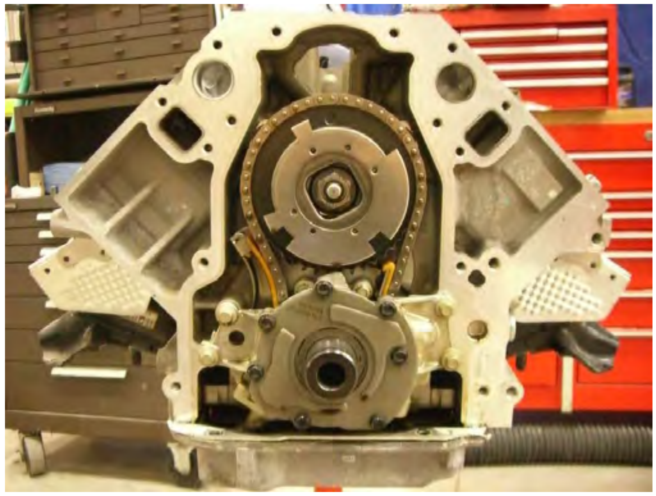


**Image 4.1-46: Silverado Timing Drive System**
*(Source: FEV, Inc.)*

### 4.1.6.3 Mass Reduction Industry Trends

Belt systems can offer a mass advantage over chains in systems with more length like dual overhead "V" configurations. Although OEMs have trended away from belts due to durability issues, belts are still common. Nylon tensioning and guide systems have replaced metal in many overhead cam timing drives (**Image 4.1-47**). These systems are lighter and less expensive than metal.

**Image 4.1-47: Nylon Tensioning and Guide System**
*(Source: http://www.iwis.de)*

Front covers or timing covers have trended to lightweight materials like magnesium or plastic. Advances in plastic technology have improved thermal resistance and coolant compatibility. Magnesium, although more expensive, has the structural capability to support accessories and mountings (**Image 4.1-48**). Plastic timing covers are common place on dry belt drive systems. Plastic timing covers on chain drive systems is a developing technology.

**Image 4.1-48: Magnesium Timing Cover - Porsche**
*(Source: http://www.gfau.com)*

#### 4.1.6.4 Summary of Mass Reduction Concepts Considered

**Table 4.1-24** lists the ideas generated for lightweighting the timing drive. As largest mass contributor, the front cover was reviewed for alternate materials. Magnesium offers a weight advantage over the base aluminum cover, but at a higher cost and mass than plastic. Plastic timing covers have been mass produced for decades on belt drive (dry) systems and offer a substantial weight savings.

The timing chain and drive gears require demanding durability characteristics. Lightweight materials such as titanium or metal matrix composites exceed cost targets; therefore, no alternatives were proposed for these components.

Although numerous examples of fully plastic guide systems are available, no cam-in-block examples were identified. At 167 grams, there is limited opportunity for lightweighting.

**Table 4.1-24: Summary of Mass Reduction Concepts Considered for Timing Drive Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Timing Chain Guide | Steel to Plastic | 60% mass reduction | Limited opportunity, no production examples for cam-in-block |
| Front Cover | Integrate into Cylinder Block | 0% mass reduction | Mass neutral |
| Front Cover | Aluminum to Plastic | 40% mass reduction | Reduced durability |
| Front Cover | Aluminum to Magnesium | 30% mass reduction | Requires coated fasteners |

#### 4.1.6.5 Selection of Mass Reduction Ideas

As seen in **Table 4.1-25**, the front cover was the only component selected for lightweighting. This single component made up a majority of the subsystem mass.

**Table 4.1-25: Mass Reduction Ideas Selected for Timing Drive Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| 01 | 08 | 00 | Timing Drive Subsystem | |
| 01 | 08 | 01 | Timing Wheels (Sprockets) | N/A |
| 01 | 08 | 02 | Tensioners | N/A |
| 01 | 08 | 03 | Guides | N/A |
| 01 | 08 | 05 | Belts, Chains | N/A |
| 01 | 08 | 06 | Covers | Front Cover - Al to Plastic |
| 01 | 08 | 99 | Misc. | N/A |
| | | | | |

The LC9 engine's diecast aluminum front cover (**Image 4.1-49**) encloses the timing drive and provides mounting for the phaser solenoid, cam timing sensor, and front crankshaft seal. The cover is exposed to engine heat and oil, and must provide accurate positioning of the crankshaft seal as well as support phaser solenoid load. The 2.4 kg of solenoid force that the cover must support is within the capabilities of plastic. Plastic can also withstand the heat and oil conditions seen in this application. Plastic front covers have been used in similar GM applications such as the 4.3L Vortec (**Image 4.1-50**). Sealing a plastic front cover may require changes to the oil pan. Mounting the cover to the front of the oil pan could save additional mass. DSM has recommend, heat stabilized, glass reinforced Stanyl® ForTii™ (PA4T-GF30) for front cover applications. To calculate mass, 20% volume was added for additional ribbing. Cost considerations were made for fastener inserts, threaded inserts and press in place gaskets to accommodate the plastic part.


**Image 4.1-49: (Left) Silverado Front Cover**
*(Source: FEV, Inc.)*

**Image 4.1-50: Plastic Front Cover 4.3L Vortech**
*(Source: http://www.gmpartsbarn.com)*

#### 4.1.6.6 Calculated Mass Reduction and Cost Impact Results

As seen in **Table 4.1-26**, changing the front cover to plastic resulted in a cost penalty. This was driven by a premium plastic selection to ensure durability. Production examples exist using less expensive polymers that could save cost.

**Table 4.1-26: Mass Reduction and Cost Impact for Timing Drive Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 01 | 08 | 00 | **Timing Drive Subsystem** | | | | | | |
| 01 | 08 | 01 | Timing Wheels (Sprockets) | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 08 | 02 | Tensioners | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 08 | 03 | Guides | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 08 | 05 | Belts, Chains | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 08 | 06 | Covers | X | 0.415 | -$2.44 | -$5.88 | 31.93% | 0.02% |
| 01 | 08 | 99 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | **X** | **0.415** (Decrease) | **-2.442** (Increase) | **-$5.88** (Increase) | **23.72%** | **0.02%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.1.7 Accessory Drive Subsystem

### 4.1.7.1 Subsystem Content Overview

Mass breakdown of the Accessory Drive Subsystem is listed in (**Table 4.1-27**). The pulleys made up a majority of subsystem mass, followed by the tensioner and serpentine belt.

**Table 4.1-27: Mass Breakdown by Sub-subsystem for Accessory Drive Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 01 | 09 | 00 | **Accessory Drive Subsystem** | |
| 01 | 09 | 01 | Pulleys | 7.270 |
| 01 | 09 | 02 | Tensioners | 0.745 |
| 01 | 09 | 03 | Guides | 0.000 |
| 01 | 09 | 05 | Belts | 0.257 |
| 01 | 09 | 99 | Misc. | 0.000 |
| | | | Total Subsystem Mass = | 8.272 |
| | | | Total System Mass = | 239.945 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 3.45% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.34% |

#### 4.1.7.2 Chevrolet Silverado Baseline Subsystem Technology

Accessory System drive components included two drive belts, belt tensioner, tensioner pulley, idler pulley, AC pulley, power steering pulley, water pump pulley, and crankshaft pulley (**Image 4.1-51**).

**Image 4.1-51: Accessory Drive Subsystem Components**
*(Source: FEV, Inc.)*

#### 4.1.7.3 Mass Reduction Industry Trends

Accessory drive pulleys, also referred to as Fiat drive pulleys, have been lightweighted using plastic and aluminum. The most recent trend is electric actuation of these components to improve efficiency. Electric power steering systems, as well as electric water pumps, are now replacing standard belt driven pumps. Electric systems are higher in cost, but only use as much crankshaft power as is needed for their functions. Belt-driven water pumps for example, continue to increase in RPM and energy consumption as the engine accelerates. However, engine cooling needs are not directly linked to RPM, but rather depend on a variety of factors like ambient temperature and payload. An electric system, in which engine temperature is electronically controlled, saves energy when cooling needs are below peak.

#### 4.1.7.4 Summary of Mass Reduction Concepts Considered

As shown in **Table 4.1-28,** pulleys were the focus of mass reduction. All pulleys had one or more lightweighting approaches suggested except the tensioner pulley which was already plastic.

**Table 4.1-28: Summary of Mass Reduction Concepts Considered for Accessory Drive Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| AC Compressor Pulley | Steel to Plastic | 60% mass reduction | Reduced durability |
| Idler Pulley | Steel to Plastic | 65% mass reduction | Established plastic application |
| Alternator Pulley | Press fit and eliminate nut | 20% mass reduction | Reduces serviceability |
| Water Pump Pulley | Lightening holes and Aluminum | 55% mass reduction | Increased Cost |
| Water Pump Pulley | Steel to Plastic | 65% mass reduction | Reduced durability |
| Power Steering Pump Pulley | Steel to Aluminum | 55% mass reduction | Increased Cost |
| Power Steering Pump Pulley | Steel to Plastic | 60% mass reduction | Reduced durability |
| Crankshaft Pulley | Cast Iron to Plastic | 75% mass reduction | Static charge dissipation issue |
| Crankshaft Pulley | Hub from cast Iron to cast Aluminum | 45% mass reduction | Requires hub insert<br>Strength Concern |

Plastic and aluminum were considered as alternatives to steel for the water pump and power steering pump pulleys. BMW's 3.0L six-cylinder has examples of both pulleys constructed from plastic (**Image 4.1-52** and **Image 4.1-53**). Plastic was not selected for lightweighting the water pump or power steering pump pulleys because greater savings could be achieved with electromechanical devices.

**Image 4.1-52 (Left): Plastic Water Pump Pulley – BMW 3.0L**
*(Source: http://www.fcpeuro.com)*

**Image 4.1-53 (Right): Plastic Power Steering Pulley – BMW 3.0L**
*(Source: http://www.ecstuning.com)*

Weighing 4.6 kg, the Silverado crankshaft pulley had significant opportunity for lightweighting. A plastic crankshaft pulley developed by Eagle Picher and DuPont™ has been built and tested for a 3.6L V6 application (**Image 4.1-54**). The plastic pulley passed durability testing but the static charge dissipation efficiency did not meet requirements. Specifics on the project and testing details were unavailable and the idea was not selected.


**Image 4.1-54: Plastic Crankshaft Pulley – Eagle Picher and DuPont**
*(Source: DuPont)*

#### 4.1.7.5 Selection of Mass Reduction Ideas

Ideas selected to lightweight the Accessory Drive Subsystem are listed in **Table 4.1-29**.

**Table 4.1-29: Mass Reduction Ideas Selected for Accessory Drive Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **09** | **00** | **Accessory Drive Subsystem** | |
| 01 | 09 | 01 | Pulleys | AC Compressor Pulley - Metal to Plastic<br>Idler Pulley - Steel to Plastic |
| 01 | 09 | 02 | Tensioners | N/A |
| 01 | 09 | 03 | Guides | N/A |
| 01 | 09 | 05 | Belts | N/A |
| 01 | 09 | 99 | Misc. | N/A |
| | | | | |

Silverado's AC compressor pulley is made from steel (**Image 4.1-55**). The 2011 Volkswagen polo has a plastic compressor pulley (**Image 4.1-56**). Volkswagen's plastic pulley is a phenol-formaldehyde (PF) thermoset with 40% glass (phenolic), providing stiffness, strength, and dimensional stability. The drawback of phenolic is its low elongation; that is, it is brittle. After reviewing this application, DuPont recommended its Zytel® HTN51LG50. This 50% long glass reinforced nylon is a heat-stabilized, lubricated polyamide resin and would outperform PF in this application. Zytel® HTN has lower density and superior mechanical properties (**Table 4.1-30**) that could improve durability. Mass for the plastic pulley was estimated by weighing a plastic AC pulley of similar size.

**Image 4.1-55 (Left): Metal AC Compressor Pulley Silverado**

**Image 4.1-56 (Right): Plastic AC Compressor Pulley Volkswagen Polo**

*(Source: FEV, Inc.)*

**Table 4.1-30: Mechanical Properties - Phenolic vs. Zytel HTN**

| Generic Identification | PF-MX.GF60 | PA66/XT-GF50 |
|---|---|---|
| Product Name | Phenolic | Zytel HTN |
| Density | 1.83 | 1.6 |
| Temp of deflect under load (°C @1.8 Mpa) | 185 | 280 |
| Coeff of linear therm exp - Parallel (10-6/°C) | 17 | 13 |
| Coeff of linear therm exp - Perpend (10-6/°C) | 41 | 42 |
| Charpy Impact Strength - Notched (kJ/m2) | 3.1 | 55 |
| Flexural strength (Mpa) | 124 | 400 |
| Flexural Modulus (Gpa) | 12 | 16.5 |
| Flexural Strain at Break (%) | 1.29 | 2.1 |
| Tensile Strength (Mpa) | 65 | 250 |
| Tensile Modulus (Gpa) | 13 | 18 |
| Tensile strain at break (%) | 0.9 | 1.5 |

The Silverado's accessory drive configuration uses a stationary idler (**Image 4.1-57**), increasing drive belt contact area with the alternator and creating clearance for the air intake. This pulley made from steel could be injection molded to save mass like the Nissan Frontier (**Image 4.1-58**). Glass-filled nylon, commonly used in idler applications, was used in this analysis. The amount of plastic required was determined by reviewing plastic idlers of similar size.

**Image 4.1-57: Idler Pulley Silverado**
*(Source: FEV, Inc.)*

**Image 4.1-58: Plastic Idler Pulley Nissan Frontier**
*(Source: http://www.haydenauto.com)*

#### 4.1.7.6 Mass Reduction and Cost Impact

**Table 4.1-31** shows the mass and cost impact for the Accessory Drive Subsystem. Substantial mass savings was gained by lightweighting pulleys. These lightweighting technologies add minimal cost to the engine.

**Table 4.1-31: Mass Reduction and Cost Impact for Accessory Drive Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | | | | | | | |
| 01 | 09 | 00 | Accessory Drive Subsystem | | | | | | |
| 01 | 09 | 01 | Pulleys | A | 1.732 | $0.73 | $0.42 | 23.82% | 0.07% |
| 01 | 09 | 02 | Tensioners | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 09 | 03 | Guides | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 09 | 05 | Belts | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 09 | 99 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | | | | | | |
| | | | | A | 1.732 (Decrease) | 0.727 (Decrease) | $0.42 (Decrease) | 20.94% | 0.07% |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.1.8 Air Intake Subsystem

#### 4.1.8.1 Subsystem Content Overview

As shown in **Table 4.1-32**, the leading mass contributor to the Air Intake Subsystem is the intake manifold followed by the air filter box.

**Table 4.1-32: Mass Breakdown by Sub-subsystem for Air Intake Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 10 | 00 | **Air Intake Subsystem** | |
| 01 | 10 | 01 | Intake Manifold | 6.038 |
| 01 | 10 | 02 | Air Filter Box | 4.501 |
| 01 | 10 | 03 | Air Filters | 0.000 |
| 01 | 10 | 04 | Throttle Housing Assembly; including Supplies | 1.193 |
| 01 | 10 | 05 | Adapters: Flanges for Port Shut-off | 0.000 |
| 01 | 10 | 99 | Misc. | 0.219 |
| | | | | |
| | | | **Total Subsystem Mass =** | **11.951** |
| | | | **Total System Mass =** | **239.945** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **4.98%** |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | **0.49%** |

### 4.1.8.2 Chevrolet Silverado Baseline Subsystem Technology

The Air Intake Subsystem consists of a variety of components used to plumb air to the engine (**Image 4.1-59**). Starting from left to right, the air comes in the lower air box, passing thru the air filter into the upper air box and then through the intake duct to the throttle body. The throttle body regulates the mass of air to the engine which is distributed to the cylinders through the intake manifold. The intake duct features multiple blow molded resonators that muffle engine noise.

**Image 4.1-59: Air Intake Subsystem Components**
*(Source: FEV, Inc.)*

All system components are made of lightweight economical nylon with exception of the aluminum throttle body and the ethylene propylene diene monomer (EPDM) rubber section of the intake duct. The intake manifold is a large, mass intensive plastic component made up of three separate injection molded sections friction welding together. The intake's long runner design delivers pressure pulses at low- to mid-range RPMs increasing volumetric efficiency and torque.

### 4.1.8.3 Mass Reduction Industry Trends

Industry trends for air intake lightweighting are focused on the intake manifold. This component, originally made from cast iron and then aluminum, are now mostly plastic. Plastic lends itself to complex and efficient dual runner designs and can even handle pressures associated with charged air systems. Aftermarket suppliers offer carbon fiber intake tubes. Due to cost, moderate density advantage, and resonator attachment points, carbon fiber was not considered.

Plastic throttle bodies are offer cost and mass advantages. Plastic applications are now emerging in vehicles such as the Mini Cooper (**Image 4.1-60**). Since bore distortion on larger throttle body housings is a limitation of plastic, it was not recommended in this application.


**Image 4.1-60 (Left): Throttle Body – Plastic Housing**

*(Source: www.greeneyeautoparts.com)*

#### 4.1.8.4 Summary of Mass Reduction Concepts Considered

As shown in **Table 4.1-33**, all plastic components were reviewed for MuCell® lightweighting. The intake manifold, weighing more than 6 kg, was a target for lightweighting. The complexity of the intake manifold made it a poor candidate for MuCell. The remaining plastic components are good applications for MuCell. The aluminum throttle body housing was reviewed for a material change to plastic. Bore distortion due to uneven thermal expansion was a concern, but paired with a compliant throttle plate design it was considered possible.

**Table 4.1-33: Summary of Mass Reduction Concepts Considered for Air Intake Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Intake Manifold | 3M Glass Bubbles | 5% mass reduction | Equivalent mechanical properties |
| Air Box | MuCell | 10% mass reduction | Reduced cycle time |
| Air Intake Duct | MuCell | 10% mass reduction | Reduced cycle time |
| Air Box Mounting Bracket | Metal to Plastic | 65% mass reduction | NVH concern |
| Throttle Body | Aluminum to Plastic | 35% mass reduction | Bore distortion |

#### 4.1.8.5 Selection of Mass Reduction Ideas

Ideas selected to lightweight the Air Intake Subsystem are listed in **Table 4.1-34**.

**Table 4.1-34: Mass Reduction Ideas Selected for Air Intake Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **10** | **00** | **Air Intake Subsystem** | |
| 01 | 10 | 01 | Intake Manifold | 3M glass bubbles |
| 01 | 10 | 02 | Air Filter Box | Air Box - MuCell<br>Air Intake Duct - MuCell<br>Air Filter Box Mount - Metal to Plastic |
| 01 | 10 | 03 | Air Filters | N/A |
| 01 | 10 | 04 | Throttle Housing Assembly; including Supplies | N/A |
| 01 | 10 | 05 | Adapters: Flanges for Port Shut-off | N/A |
| 01 | 10 | 99 | Misc. | N/A |
| | | | | |

The base intake manifold (**Image 4.1-61**), was constructed from Nylon 6 and lightweighted using 3M Glass Bubbles.

**Image 4.1-61: Intake Manifold, Silverado**

*(Source: FEV, Inc.)*

Following an application review with 3M, Glass Bubbles were selected because of their unique ability to reduce density while maintaining strength. 3M's iM16K Glass Bubble was added to the base Nylon at a 5% weight ratio, reducing density by 6%. With the addition of a MAPP compatibilizer, mechanical properties are nearly equal, with some characteristics even improving. **Table 4.1-35** provides a comparison of mechanical properties for PA66 GF20, with and without Glass Bubbles (includes MAPP stabilizer).

**Table 4.1-35: PA66 GF20 Mechanical Properties Comparison – Glass Bubbles**

| Component | Formula 1 | | Formula 4 | |
|---|---|---|---|---|
| | 20wt%GF | | 20wt% GF 5 wt% iM16K w/MAPP | |
| | Wt% | Vol% | Wt% | Vol% |
| Homopolymer PP | 80 | 92.07 | 72 | 78.48 |
| Glass Fiber | 20 | 7.93 | 20 | 7.51 |
| iM30K-GB | | | | |
| iM16K-GB | | | 5 | 10.67 |
| MAPP | | | 3 | 3.34 |
| **Final** | **100** | **100** | **100** | **100** |
| Density | 1.054 | | 0.99 | |
| Tensile Strength (Mpa) | 76.9 | | 72 | |
| Tensile Elongation (%) | 3.61 | | 3.9 | |
| Tensile Modulus (Mpa) | 3530 | | 3520 | |
| Flexural Strength (Mpa) | 98.6 | | 105 | |
| Flexural Modulus (Mpa) | 2730 | | 2758 | |
| Izod impact Strength at RT (J/m) | 6380 | | 6000 | |

Glass Bubbles selected for this application are hollow, thin wall unicellular spheres, 31 microns or less in diameter and .72 microns in wall thickness with a crush strength of 16.5 ksi (**Image 4.1-62**). Other known applications extend through the vehicle from plastic body covers and molding to underbody seam and sealer.

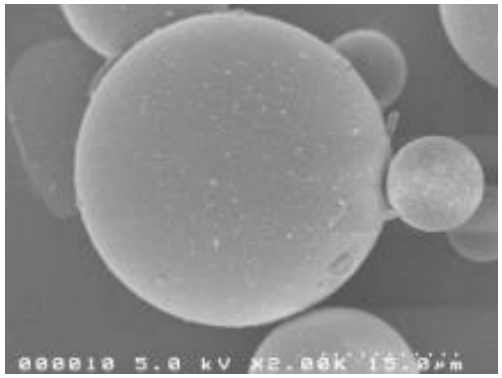



**Image 4.1-62: 3M Glass Bubble iM16K**
*(Source: 3M image)*

After consulting Trexel, MuCell was applied to all applicable intake components (**Image 4.1-63**). Due to the basic geometry of these components, material delivery webs could not be thinned and a 9% mass reduction was applied. MuCell technology is currently used by major OEMs such as Audi, Ford, BMW and Volkswagen, as introduced in section **4.3.1.2**.

**Image 4.1-63: Air Box Lower/Upper and Air Intake Duct MuCell - 9% Mass Savings**
*(Source: FEV, Inc.)*

#### 4.1.8.6 Mass Reduction and Cost Impact

**Table 4.1-36** shows the weight and cost savings for Air Intake lightweighting. The changes made to the Air Intake Subsystem result in an overall cost savings.

**Table 4.1-36: Mass Reduction and Cost Impact for Air Intake Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | | | | | | | |
| **01** | **10** | **00** | **Air Intake Subsystem** | | | | | | |
| 01 | 10 | 01 | Intake Manifold | D | 0.278 | -$0.81 | -$2.92 | 4.60% | 0.01% |
| 01 | 10 | 02 | Air Filter Box | A | 0.663 | $0.27 | $0.40 | 14.74% | 0.03% |
| 01 | 10 | 03 | Air Filters | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 10 | 04 | Throttle Housing Assembly; including Supplies | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 10 | 05 | Adapters: Flanges for Port Shut-off | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 10 | 99 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | | | | | | |
| | | | | B | **0.941** (Decrease) | **-0.542** (Increase) | **-$0.58** (Increase) | **7.88%** | **0.04%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.1.9 Fuel Induction Subsystem

#### 4.1.9.1 Subsystem Content Overview

**Table 4.1-37** details the mass breakdown for the Fuel Induction Subsystem. The most significant subsystem mass contributor is the fuel rail. The fuel injection pump and regulator were included in the Fuel System and therefore excluded from the Fuel Induction Subsystem. At 1.12 kg, this subsystem had a minimum impact on the overall Engine System mass.

**Table 4.1-37: Mass Breakdown by Sub-subsystem for Fuel Induction Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 11 | 00 | Fuel Induction Subsystem | |
| 01 | 11 | 01 | Fuel Rails | 0.858 |
| 01 | 11 | 04 | Fuel Injectors | 0.264 |
| 01 | 11 | 06 | Pressure Regulators | 0.000 |
| 01 | 11 | 07 | Fuel Injection Pumps | 0.000 |
| 01 | 11 | 99 | Misc. | 0.000 |
| | | | | |
| | | | Total Subsystem Mass = | 1.122 |
| | | | Total System Mass = | 239.945 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 0.47% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.05% |

#### 4.1.9.2 Silverado Baseline Subsystem Technology

The Silverado Fuel Induction System consists of a fuel rail and fuel injectors (**Image 4.1-64**). The fuel system is returnless, meaning the regulator is located in the fuel tank. A returnless system eliminates the need for a return fuel line and minimizes tank fuel temperature reducing evaporation.

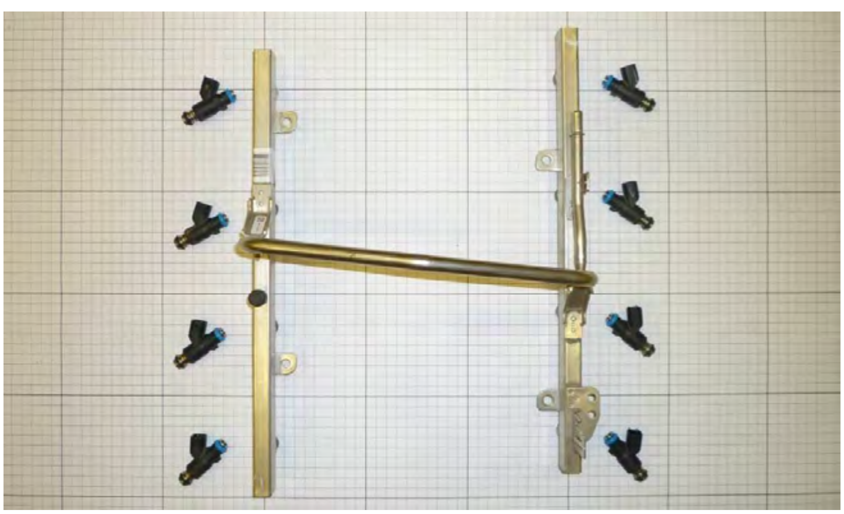


**Image 4.1-64: Fuel Induction Subsystem Components**
*(Source: FEV, Inc.)*

#### 4.1.9.3 Mass Reduction Industry Trends

Fuel induction lightweighting trends include smaller more efficient fuel injectors and lightweight plastic fuel rails. Plastic fuel rails need to be protected in the event of crash and are often found on V engines. Compatibility issues arise with plastic fuel rails and flex fuel. **Image 4.1-65** shows a plastic 5.3L fuel rail for GM engines not equipped with Flex Fuel. Due to tightened emissivity regulations and flex fuel requirements, plastic was not considered for Silverado.

**Image 4.1-65: Fuel Rail with Integrated Pulsation Dampener**
*(Source: FEV, Inc.)*

#### 4.1.9.4 Summary of Mass Reduction Concepts Considered

No mass reduction concepts were generated for the Fuel Induction Subsystem.

### 4.1.10 Exhaust Subsystem

#### 4.1.10.1 Subsystem Content Overview

As seen in **Table 4.1-38,** the only components included in the Exhaust Subsystem are related to the exhaust manifolds. All other exhaust related components are included in the Exhaust System.

**Table 4.1-38: Mass Breakdown by Sub-subsystem for Exhaust Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 12 | 00 | **Exhaust Subsystem** | |
| 01 | 12 | 01 | Exhaust Manifold | 12.166 |
| 01 | 12 | 04 | Collector Pipes | 0.000 |
| 01 | 12 | 05 | Catalysts | 0.000 |
| 01 | 12 | 06 | Particle Filters | 0.000 |
| 01 | 12 | 07 | Silencers (Mufflers) | 0.000 |
| 01 | 12 | 08 | Oxygen Sensors | 0.000 |
| 01 | 12 | 99 | Misc. | 0.000 |
| | | | | |
| | | | **Total Subsystem Mass =** | **12.166** |
| | | | **Total System Mass =** | **239.945** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **5.07%** |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | **0.50%** |

### 4.1.10.2 Silverado Baseline Subsystem Technology

**Image 4.1-66** shows the Silverado exhaust manifolds with heat shields and gaskets. Cast iron exhaust manifold, as found on the Silverado, are the most common type of exhaust found on cars and trucks. Low cost, sound absorption, and heat insulating are among the advantages of cast iron. The downside to cast iron is its considerable mass as compared with alternatives.

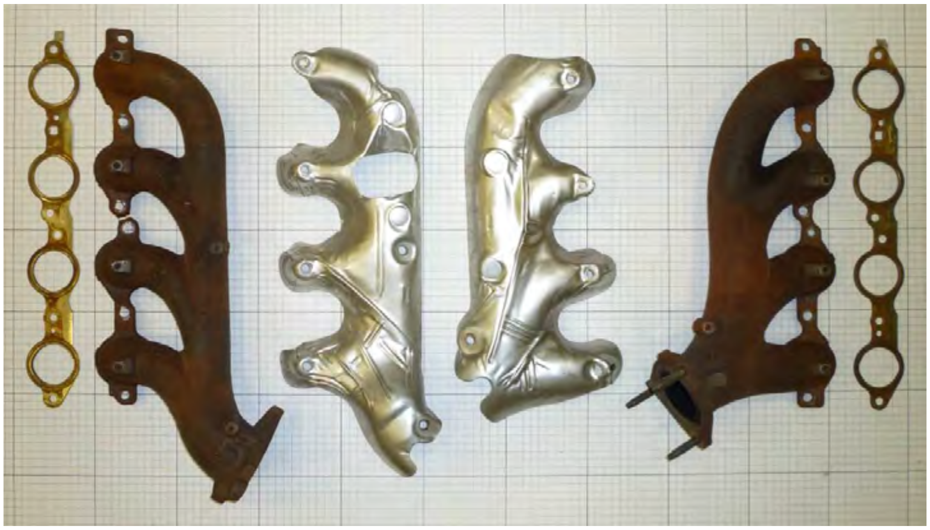


**Image 4.1-66: Exhaust Subsystem Components**
*(Source: FEV, Inc.)*

### 4.1.10.3 Mass reduction Industry Trends

Manifold catalysts (**Image 4.1-67**), developed for improved light off times and reduced emissions, are lighter than a traditional cast iron manifolds. Either mandrel bent tube or stamped or welded (**Image 4.1-68**) thinner wall sections provide a mass advantage over cast iron. Fabricated manifolds with integrated catalyst are common for quick light off and improved emissions.

**Image 4.1-67: (Left) Fabricated V8 Exhaust Manifold (LS7 Corvette)**
*(Source: http://www.ebay.com)*

**Image 4.1-68: (Right) Fabricated Exhaust Manifold**
*(Source: http://www.ddperformanceresearch.com)*

### 4.1.10.4 Summary of Mass Reduction Concepts Considered

As shown in **Table 4.1-39**, lightweighting options considered for the exhaust manifolds were changing to a steel fabricated manifold and integrated exhaust manifold as shown in

**Image 4.1-69**. Integrated exhaust manifold (IEM) offers a substantial mass savings as well as cost savings, however combustion imbalance with V8 firing order prohibits this technology. IEM Production examples include GM 3.6L LFX, Honda 2.4L, and Ford 1.5L EcoBoost.

**Image 4.1-69 (Right): Integrated Exhaust Manifold**
*(Source: http://green.autoblog.com)*

**Table 4.1-39: Summary of Mass Reduction Concepts Considered for Exhaust Subsystem**

Exhaust Subsystem

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Exhaust Manifold | Solid cast to tubular weldment | 45% mass reduction | Increased heat radiation |
| Exhaust Manifold | Integrate into cylinder head | 45% mass reduction | not suitable for airflow separation requirement with V8 firing order |

### 4.1.10.5 Selection of Mass Reduction Ideas

Ideas selected to lightweight the Exhaust Subsystem are listed in **Table 4.1-40**.

**Table 4.1-40: Mass Reduction Ideas Selected for Exhaust Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **12** | **00** | **Exhaust Subsystem** | |
| 01 | 12 | 01 | Exhaust Manifold | dual wall fabricated manifold |
| 01 | 12 | 04 | Collector Pipes | N/A |
| 01 | 12 | 05 | Catalysts | N/A |
| 01 | 12 | 06 | Particle Filters | N/A |
| 01 | 12 | 07 | Silencers (Mufflers) | N/A |
| 01 | 12 | 08 | Oxygen Sensors | N/A |
| 01 | 12 | 99 | Misc. | N/A |
| | | | | |

The Silverado's exhaust manifolds (**Image 4.1-70**) were lightweighted by replacing the cast iron components with a stainless steel fabricated assembly. Tenneco a supplier of fabricated manifolds designed a direct replacement manifold for the Chevrolet Silverado. This concept has been prototyped (Image 4.1-76). The inner wall (Image 4.1-77) being 1mm thick and the outer wall (Image 4.1-78)  1.5mm thick. Both austenitic and ferritic grades of stainless steel are used in fabricated manifolds. Manufacturing processes include hydroforming, stamping, welding, and brazing. Production examples of fabricated manifolds include the Toyota Avensis 2.0-R4 4V and LS7 Corvette. Fabricated manifolds require heat shielding. (*http://wardsauto.com/ar/tenneco_manifold_destiny_110923*)

**Image 4.1-70: Silverado Cylinder Head and Exhaust Manifold**
*(Source: FEV, Inc.)*

**Image 4.1-76: Silverado Fabricated Exhaust Manifold Concept Prototype**
*(Source: Tenneco)*

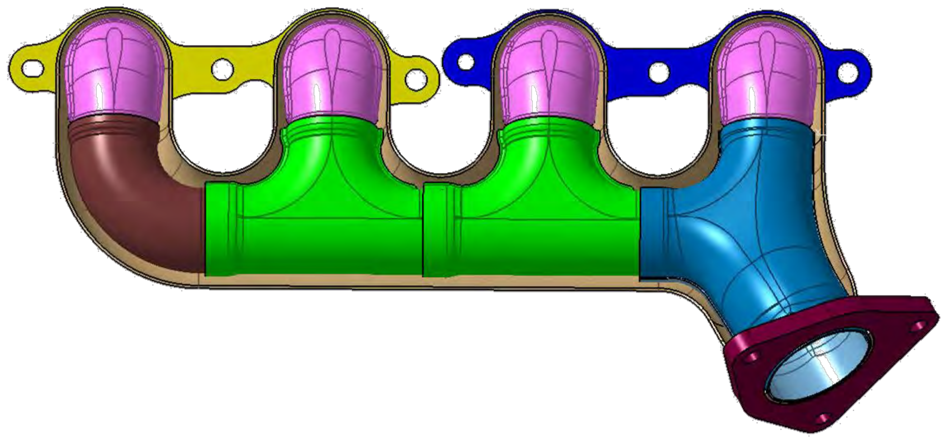


**Image 4.1-77: Silverado Fabricated Exhaust Manifold Concept (Inner Construction)**
*(Source: Tenneco)*

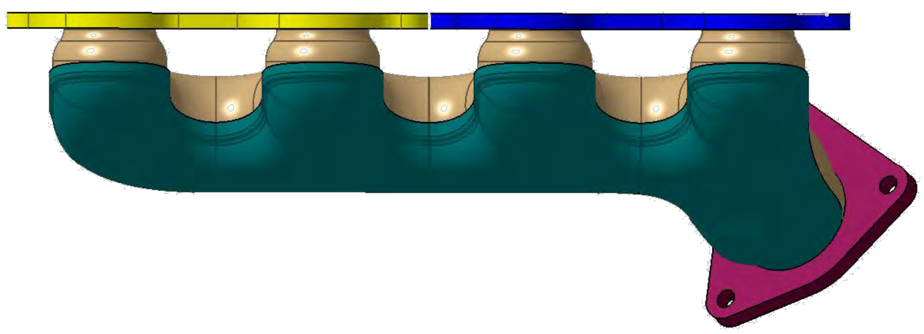


**Image 4.1-78: Silverado Fabricated Exhaust Manifold Concept (Inner Construction)**
*(Source: Tenneco)*

### 4.1.10.6 Mass Reduction and Cost Impact

**Table 4.1-41** shows the mass and cost impact for the Exhaust Subsystem. Replacing cast iron exhaust manifolds with fabricated manifolds represented the largest single mass reduction on the engine. The cast iron manifold weight for driver and passenger sides are 5.35kg and 5.60kg respectively. Tenneco's fabricated manifolds, including downpipe flange, weigh 3.80 and 4.00 kg. Fabricated manifold costs used in this study were surrogate cost developed for similar manifolds and did not come from Tenneco.

**Table 4.1-41: Mass Reduction and Cost Impact for Exhaust Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 01 | 12 | 00 | **Exhaust Subsystem** | | | | | | |
| 01 | 12 | 01 | Exhaust Manifold | X | 3.148 | -$20.00 | -$6.35 | 25.88% | 0.13% |
| 01 | 12 | 04 | Collector Pipes | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 12 | 05 | Catalysts | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 12 | 06 | Particle Filters | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 12 | 07 | Silencers (Mufflers) | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 12 | 08 | Oxygen Sensors | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 12 | 99 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | **X** | **3.148** (Decrease) | **-20.000** (Increase) | **-$6.35** (Increase) | **25.88%** | **0.13%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.1.11 Lubrication Subsystem

### 4.1.11.1 Subsystem Content Overview

As seen in **Table 4.1-42**, the largest contributor to the Lubrication Subsystem is the oil pan. Included within the Miscellaneous Sub-subsystem is the dipstick assembly.

**Table 4.1-42: Mass Breakdown by Sub-subsystem for Lubrication Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 01 | 13 | 00 | **Lubrication Subsystem** | |
| 01 | 13 | 01 | Oil Pans (Oil Sump) | 7.776 |
| 01 | 13 | 02 | Oil Pumps | 2.061 |
| 01 | 13 | 05 | Pressure Regulators | 0.000 |
| 01 | 13 | 06 | Oil Filter | 0.424 |
| 01 | 13 | 99 | Misc. | 0.286 |
| | | | **Total Subsystem Mass =** | **10.547** |
| | | | **Total System Mass =** | **239.945** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **4.40%** |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | **0.43%** |

#### 4.1.11.2 Silverado Baseline Subsystem Technology

The Silverado oil pump is a generated rotor ("gerotor") design. The Inner rotor is driven on center with the crankshaft while the outer rotor rotates off center in a housing bolted to the front of the engine block. The oil pump houses the pressure regulator. A series of baffle plates, one mounted in the lower sump and one mounted under the crankshaft, reduce oil turbulence. The oil pan is a diecast aluminum component and provides a stiffening element to the engine block assembly. Other components include the oil pick-up, dip stick assembly, and oil filter neck/cap (**Image 4.1-71**).

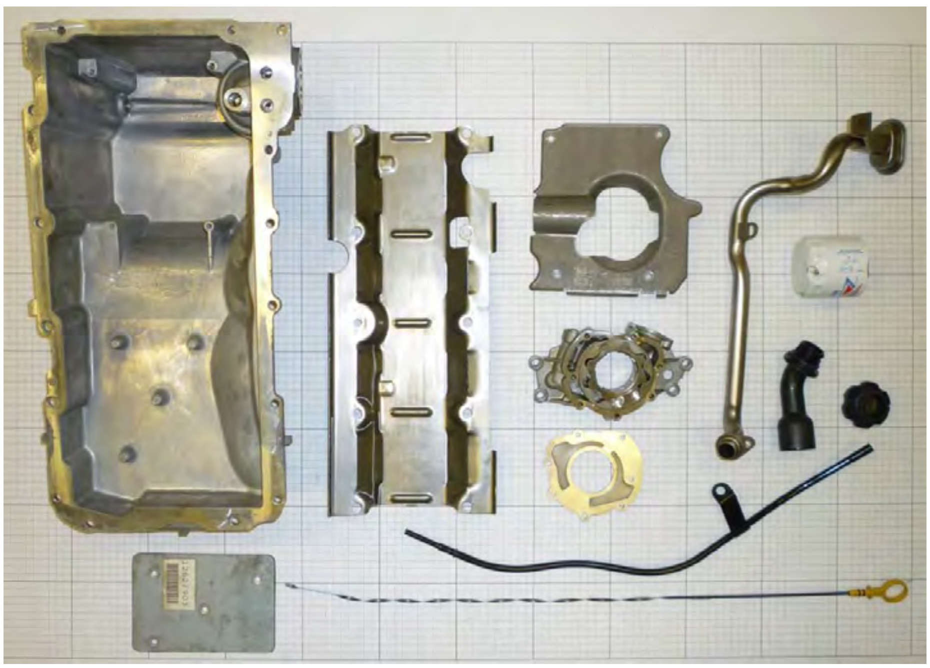


**Image 4.1-71: Lubrication Subsystem Components**
*(Source: FEV, Inc.)*

#### 4.1.11.3 Mass Reduction Industry Trends

Lightweighting trends for lubrication systems are metal-to-plastic applications. Common components include oil pans, baffle plates, and dip stick cases. Plastic presents the best advantage when multiple components can be integrated into one, such as the oil filter mount and the oil pan. Another lightweighting approach is to integrate the oil pump housing into the front cover.

### 4.1.11.4 Summary of Mass Reduction Concepts Considered

**Table 4.1-43** summarizes ideas considered for the Lubrication Subsystem. Plastic was considered for the oil pan but was eliminated as it is a structural member of the engine. Silverado's oil pump cover is a steel plate that could be made from aluminum to save mass. Without specification and operating parameters this change was considered a risk due to the differences in wear between steel and aluminum. The oil filter was reviewed for mass savings by changing to a replaceable element with plastic housing. Detailed comparison reviled the change is mass neutral however the replaceable element type is more environmentally friendly. Some engine architectures support using a breather passage as a dipstick tube, eliminating that component. The Silverado's engine design does not permit this dual function.

Austrian supplier Schneegans Silicon GmbH supplies a plastic dip stick tube for BMW's 2L diesel engine (**Image 4.1-72**). Water-injection technology and DuPont™ Zytel® nylon produce a lightweight economical alternative to steel. Plastic also allows easy integration of surrounding components. The Silverado dip stick tube is located in close proximity to the exhaust system making this technology incompatible with the current architecture.

**Image 4.1-72: Plastic Dip Stick Tube (BMW 2L Diesel)**

*(Source: http://plastics.dupont.com)*

**Table 4.1-43: Summary of Mass Reduction Concepts Considered for Lubrication Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Oil Pan | Aluminum to Plastic | 30% mass reduction | Structural member |
| Oil Pan | Aluminum to Magnesium | 25% mass reduction | Reduced stiffness |
| Crank Cover Baffle Plate | Steel to Plastic | 70% mass reduction | Reduced stiffness |
| Oil Pan Gasket | Aluminum to Rubber inlay | 60% mass reduction | Sealing risk |
| Oil Pick-up Tube | Steel to Plastic | 65% mass reduction | Gas assist molding required |
| Oil Pump Cover | Steel to Aluminum | 55% mass reduction | Aluminum wear surface |
| Oil Filter | Standard to replaceable paper element | 0% mass reduction | Mass neutral |
| Dip Stick Tube | integrate into breather passage | 0% mass reduction | Breather passages not suitable housing for dipstick |
| Dip Stick Tube | Steel to Plastic | 60% mass reduction | Reduced durability/Heat |

#### 4.1.11.5 Selection of Mass Reduction Ideas

**Table 4.1-44** summarizes the Ideas Implemented for the Lubrication Subsystem.

**Table 4.1-44: Mass Reduction Ideas Selected for Lubrication Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **13** | **00** | **Lubrication Subsystem** | |
| 01 | 13 | 01 | Oil Pans (Oil Sump) | Oil Pan - Aluminum to Magnesium<br>Windage Trays - Steel to Plastic |
| 01 | 13 | 02 | Oil Pumps | Oil Pick Up Tube - Steel to Plastic |
| 01 | 13 | 05 | Pressure Regulators | N/A |
| 01 | 13 | 06 | Oil Filter | N/A |
| 01 | 13 | 99 | Misc. | Dip Stick Tube - Stamped Steel to Plastic |
| | | | | |

Magnesium was selected as a lightweighting option for the Silverado structural oil pan (**Image 4.1-73**). The density advantage of magnesium on this large casting can save significant mass. Magnesium's lower stiffness would require structural sections of the pan to be thickened. The relationship between section thickness and strength is exponential, quickly regaining lost stiffness. Clearance for larger section thickness was reviewed and does not appear to be an issue on the Silverado. Specific changes to structural elements needed to determine oil pan mass require full design details and FEA tools. Using surrogate data from other aluminum to magnesium changes on components like transmission housings indicates 25% mass reduction is achievable. The Nissan GTR is an example of a structural magnesium oil pan (**Image 4.1-74**). Specialized fasteners required for use with magnesium were included in this cost build up.


**Image 4.1-73 (Left): Aluminum Oil Pan Silverado**
*(Source: FEV, Inc.)*

**Image 4.1-74 (Right): Magnesium Oil Pan Nissan GTR**
*(Source: http://victorianissannews.com)*

Stamped steel oil baffle plates are used to reduce turbulence and fluid restriction of moving parts. Preventing unintended grabbing of pan oil helps keep the oil pick-up submerged, particularly at high RPM. These plates, otherwise known as windage trays (**Image 4.1-75**), can be made from light-weight plastic. The 2011 Ford Mustang 5.0L features a plastic windage tray (**Image 4.1-76**). Plastic mass was estimated by assuming an average 3.00 mm thickness.

**Image 4.1-75 (Left): Silverado Windage Tray**

*(Source: FEV, Inc.)*

**Image 4.1-76 (Right): Ford 5.0L Windage Tray**

*(Source: http://www.drivingenthusiast.net)*

The Silverado's oil pick-up (**Image 4.1-77**) consists of a steel tube with welded brackets. Oil pick-up is a good application for plastic. Production examples include the Ford Focus (**Image 4.1-78**) and eight-cylinder, 4.0L Jaguar. Plastic component mass was estimated by doubling the metal components volume and applying the density of plastic. Plastic requires component redesign.

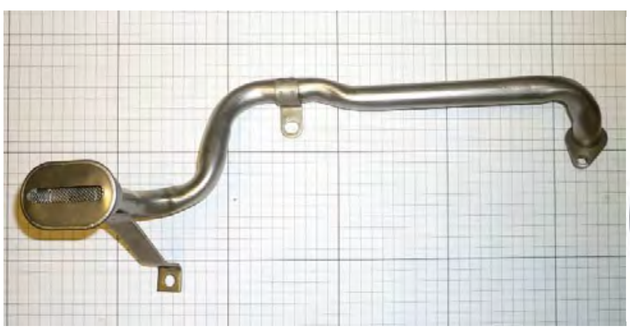


**Image 4.1-77 (Left): Silverado Oil Pick-Up Tube**

*(Source: FEV, Inc.)*

**Image 4.1-78 (Right): Focus Oil Pick-up Tube**

*(Source: http://www.oreillyauto.com.)*

#### 4.1.11.6 Mass Reduction and Cost Impact

As seen in **Table 4.1-45**, the largest mass saving was found in the Oil Pans Sub-subsystem, which includes the oil pan baffle plate. Results for the dip stick tube are listed in the Miscellaneous Sub-subsystem. Lightweighting the Lubrication Subsystem increases engine cost.

**Table 4.1-45: Mass reduction and Cost Impact for Lubrication Subsystem**

*(See Appendix for Additional Cost Detail)*

| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction Idea | | | | | |
| 01 | 13 | 00 | **Lubrication Subsystem** | | | | | | |
| 01 | 13 | 01 | Oil Pans (Oil Sump) | D | 2.580 | -$11.29 | -$4.37 | 33.18% | 0.11% |
| 01 | 13 | 02 | Oil Pumps | A | 0.429 | $0.04 | $0.00 | 20.82% | 0.02% |
| 01 | 13 | 05 | Pressure Regulators | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 13 | 06 | Oil Filter | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 13 | 99 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | D | **3.009** (Decrease) | **-11.242** (Increase) | **-$3.74** (Increase) | **28.53%** | **0.12%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.1.12 Cooling Subsystem

#### 4.1.12.1 Subsystem Content Overview

**Table 4.1-46** summarizes the mass breakdown for the Cooling Subsystem. The largest mass contributor is the radiator. Included in the Heat Exchanger Sub-subsystem is the cooling fan assembly and oil cooler line set.

**Table 4.1-46: Mass Breakdown by Sub-subsystem for Cooling Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 14 | 00 | Cooling Subsystem | |
| 01 | 14 | 01 | Water Pumps | 4.683 |
| 01 | 14 | 02 | Thermostat Housings | 0.315 |
| 01 | 14 | 04 | Heat Exchangers | 14.230 |
| 01 | 14 | 05 | Pressure Regulators | 0.000 |
| 01 | 14 | 06 | Expansion Tanks | 1.219 |
| 01 | 14 | 99 | Misc. | 3.875 |
| | | | | |
| | | | Total Subsystem Mass = | 24.322 |
| | | | Total System Mass = | 239.945 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 10.14% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.99% |

#### 4.1.12.2 Silverado Baseline Subsystem Technology

The Silverado radiator (**Image 4.1-79**) uses a standard aluminum heat transfer element with plastic end caps on each side. The water pump is aluminum and integrates thermostat mounting. The water pump pulley is steel and the thermostat housing is aluminum.

**Image 4.1-79: Silverado Cooling Subsystem**
*(Source: FEV, Inc.)*

### 4.1.12.3 Mass Reduction Industry Trends

Lightweighting trends for the Cooling System include the use of plastic water pump housings, plastic water pump impellers, and plastic thermostat housings. Coolant transfer tubes are now being manufactured from plastic. Water pump impeller housings typically constructed in aluminum are now being manufactured from plastic (**Image 4.1-80**). Possessing lighter weight and lower cost, these housings are an attractive alternative to metal. Transmission heat exchangers assembled in the radiator are now being made from lightweight aluminum (**Image 4.1-81**) instead of copper alloy (**Image 4.1-82**) and can save 50% mass.

**Image 4.1-80: Water Pump Impeller Housing - Plastic**
*(Source: new.minimania.com)*

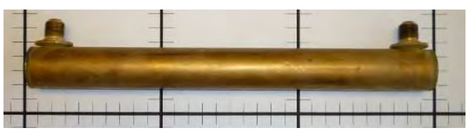


**Image 4.1-81 (Left): Transmission Heat Transfer Element – Copper Alloy**

**Image 4.1-82 (Right): Transmission Heat Transfer Element – Aluminum Alloy**
*(Source: FEV, Inc.)*

### 4.1.12.4 Summary of Mass Reduction Concepts Considered

Lightweighting ideas considered for the Cooling System are summarized in **Table 4.1-47**.

**Table 4.1-47: Summary of Mass Reduction Concepts Considered for Cooling Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Water Pump | Aluminum to Plastic | 35% mass reduction | Belt load exceeds material stiffness |
| Water Pump | Aluminum to two piece Aluminum and Plastic | 20% mass reduction | Sealing and durability concerns |
| Water Pump | Mechanical to electric | 55% mass reduction | substantial cost, improved efficiency |
| Water Pump Impeller | Steel to Plastic | 55% mass reduction | Established plastic application |
| Thermostat Housing | Aluminum to Plastic | 50% mass reduction | Established plastic application |
| Cooling Fan Housing | MuCell | 15% mass reduction | Established MuCell application, section reductions possible. |
| Cooling Fan Blades | MuCell | 7% mass reduction | Potential balancing issue |
| External Coolant Lines | Steel to Plastic | 0% mass reduction | No mass savings, reduced durability |
| Radiator | Downsize | 15% mass reduction | Application specific design could effect cost |

The Silverado's water pump is a mass intensive component and was the focus of this subsystem. The water pump function of flowing coolant, housing the impellar, and housing the thermostat can be facilitated by plastic. The loads imposed on the housing from the drive belt were a concern for plastic and theirfore a two piece design was considered. Aluminum could be used for the structual element and plastic to house the plumbing and thermostat. In addition to sealability concerns, no examples of such a concept could be found and a major design effort would be required for validation. Integration of a drive motor rather than a drive belt reduces the structural demand seen by the waterpump housing. Plastic coolant lines have been successful in replacing EPDM in select applications. No applications for plastic cooling lines were identified on the Silverado.

#### 4.1.12.5 Selection of Mass Reduction Ideas

**Table 4.1-48** summarizes lightweighting ideas selected for the Cooling Subsystem.

**Table 4.1-48: Mass Reduction Ideas Selected for Cooling Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **14** | **00** | **Cooling Subsystem** | |
| 01 | 14 | 01 | Water Pumps | Water Pump - Mechanical to Electric |
| 01 | 14 | 02 | Thermostat Housings | N/A |
| 01 | 14 | 04 | Heat Exchangers | Radiator - Downsize for specific application<br>Fan Shroud/Fan Blades - MuCell |
| 01 | 14 | 05 | Pressure Regulators | N/A |
| 01 | 14 | 06 | Expansion Tanks | N/A |
| 01 | 14 | 99 | Misc. | N/A |
| | | | | |

Electric water pumps can be found on a variety of vehicles. BMW's 328, 528, and X3/5 use a Pierburg electric water pump (EWP) for primary engine cooling rather than a traditional belt-driven pump (**Image 4.1-83**). Other applications include after-run pumps associated with turbo charging and battery cooling systems such as the Chevrolet Volt. At 2.0 kg, a Pierburg CWA400 saves significant mass over Silverado's 4.7 kg belt driven pump. EWPs have been a popular SBC aftermarket upgrade for years with the key advantage of freeing crankshaft power (**Image 4.1-84**).

**Image 4.1-83 (Left): Electric Water Pump Pierburg CWA 400**

*(Source: www.pressebox.com)*

**Image 4.1-84 (Right): Small Block Chevrolet Electric Water Pump - Proform**

*(Source: paceperformance.com)*

Davies Craig is an aftermarket supplier of electric water pumps and offers a variety of pump sizes. Marketed for primary cooling of high output V8 engines, Davies Craig recommends its EWP150. This is a 150liter per hour pump currently offered in an aluminum offered with aluminum housing and total pump weight of 1.815 kg. As with their EWP115 pump Davies Craig thinks the EWP150 could also utilize a lightweight plastic housing reducing pump weight to 1.515 kg. Davies is developing a brushless alternative to this permanent magnet motored pump, increasing life from 3,000 hours to the production automotive 9,000 hour standard. With plastic housing this pump saves and estimated 3.2 kg over base Silverado (**Image 4.1-85)**. Mass savings and cost calculation includes; Nylon housed brushless EWP150 concept, isolator mount, mount bracket, controls/wiring, additional alternator capacity, hose fittings, and map thermostat. As part of this study a EWP115 was purchased and reviewed for cost (**Image 4.1-86**). Results were scaled up to the 150 liter EWP150 and brushless motor costs were used. Electric water pump applications can be optimized by designing low pressure drop systems reducing pump requirements. Davies Craig estimates that freeing up crankshaft power saves up to 10 kW and an estimated 3.5-10% fuel savings. Due to the current high costs of electric water pumps this technology is not feasible for lightweighting alone; however, when combined with efficiency improvements this technology will likely continue to gain market share.

**Image 4.1-85 (Left): Silverado Water Pump and Pulley**

*(Source: FEV, Inc.)*

**Image 4.1-86 (Right): Davies Craig EWP115**

*(Source: https://merlinmotorsport.co.uk)*

Like many components found on Silverado, the radiator is shared by other vehicle applications such as Yukon Denali XL, Escalade, and Suburban. These vehicles feature 6.0L engines with more output than Silverado and increased curb weight. A radiator specifically built for the Silverado application could be made smaller. Using the displacement difference of 10% between the 5.3L and 6.0L and estimated 1.1 kg of radiator and fluid mass could be saved.

Some sections of the fan shroud (**Image 4.1-87**) are designed for material flow. Due to the improved flow characteristics of MuCell, these sections can be thinned to their structural requirement making the fan shroud a good candidate for MuCell and savings of 15% mass. The radiator fans were also applied with MuCell, which may require balancing. MuCell technology is currently used by major OEM's like, Audi, Ford, BMW, and Volkswagen as introduced in **Section 4.3.1**.

**Image 4.1-87 Fan Shroud: MuCell 15% Mass Savings; Fan Blades: MuCell 7% Mass Savings)**

*(Source: FEV, Inc.)*

### 4.1.12.6 Calculated Mass Reduction and Cost Impact Results

As seen in **Table 4.1-49**, changes made to the Cooling Subsystem resulted in a significant cost penalty. As stated in the section above when evaluating the feasibility of electric water pumps, the value of improved efficiency must be considered. Cost estimation for the electric water pump is based on manufacturing costs without any new technology premiums. Facilitating the electric water pump is a MAP thermostat outweighing Silverado's standard thermostat and housing. The additional cost of the MAP thermostat is included in the Water Pump Sub-subsystem. MuCell and radiator downsizing both reduced cost. Cost penalties for a radiator custom to Silverado were not considered in the downsizing cost calculation.

**Table 4.1-49: Mass Reduction and Cost Impact for Cooling Subsystem**
*(See Appendix for Additional Cost Detail)*

| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction Idea | | | | | |
| 01 | 14 | 00 | Cooling Subsystem | | | | | | |
| 01 | 14 | 01 | Water Pumps | X | 2.431 | -$94.12 | -$38.71 | 51.91% | 0.10% |
| 01 | 14 | 02 | Thermostat Housings | A | -0.229 | $0.00 | $0.00 | -72.77% | -0.01% |
| 01 | 14 | 04 | Heat Exchangers | A | 1.059 | $2.16 | $2.04 | 7.45% | 0.04% |
| 01 | 14 | 05 | Pressure Regulators | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 14 | 06 | Expansion Tanks | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 14 | 99 | Misc. | A | 0.053 | -$0.10 | $0.00 | 1.37% | 0.00% |
| | | | | X | 3.314 (Decrease) | -92.063 (Increase) | -$27.78 (Increase) | 13.63% | 0.14% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.1.13 Induction Air Charging Subsystem

Silverado's 5.3L engine is naturally aspirated with no induction air charging system.

### 4.1.14 Exhaust Gas Re-circulation Subsystem

No lightweighting solutions were identified in the Silverado EGR Subsystem.

### 4.1.15 Breather Subsystem

#### 4.1.15.1 Subsystem Content Overview

No lightweighting solutions were identified on the Silverado Breather Subsystem.

### 4.1.16 Engine Management, Engine Electronic, and Electrical Subsystem

#### 4.1.16.1 Subsystem Content Overview

As seen in **Table 4.1-50**, Engine Electrical Sub-subsystems includes the ignition coils and brackets making up a majority of the subsystem mass. The engine wiring harness is included in *System 18: Electrical Distribution and Electrical Control*.

**Table 4.1-50: Mass Breakdown by Sub-subsystem for Engine Management, Engine Electronic, and Electrical Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 01 | 60 | 00 | Engine Management, Engine Electronic, Electrical Subsystem | |
| 01 | 60 | 01 | Spark Plugs, Glow Plugs | 0.328 |
| 01 | 60 | 02 | Engine Management Systems, Engine Electronic Systems | 1.280 |
| 01 | 60 | 03 | Engine Electrical Systems (including Wiring Harnesses, Earth Straps, Ignition Harness, Coils, Sockets) | 4.062 |
| 01 | 60 | 99 | Misc. | 0.000 |
| | | | **Total Subsystem Mass =** | 5.670 |
| | | | **Total System Mass =** | 239.945 |
| | | | **Total Vehicle Mass =** | 2454 |
| | | | **Subsystem Mass Contribution Relative to System =** | 2.36% |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | 0.23% |

### 4.1.16.2 Chevrolet Silverado Baseline Subsystem Technology

The Engine Management, Engine Electronic, Electrical Subsystem includes the ECM, ECM brackets, sensors, coils, coil brackets, coils (not pictured) and spark plugs (not pictured) (**Image 4.1-88**).

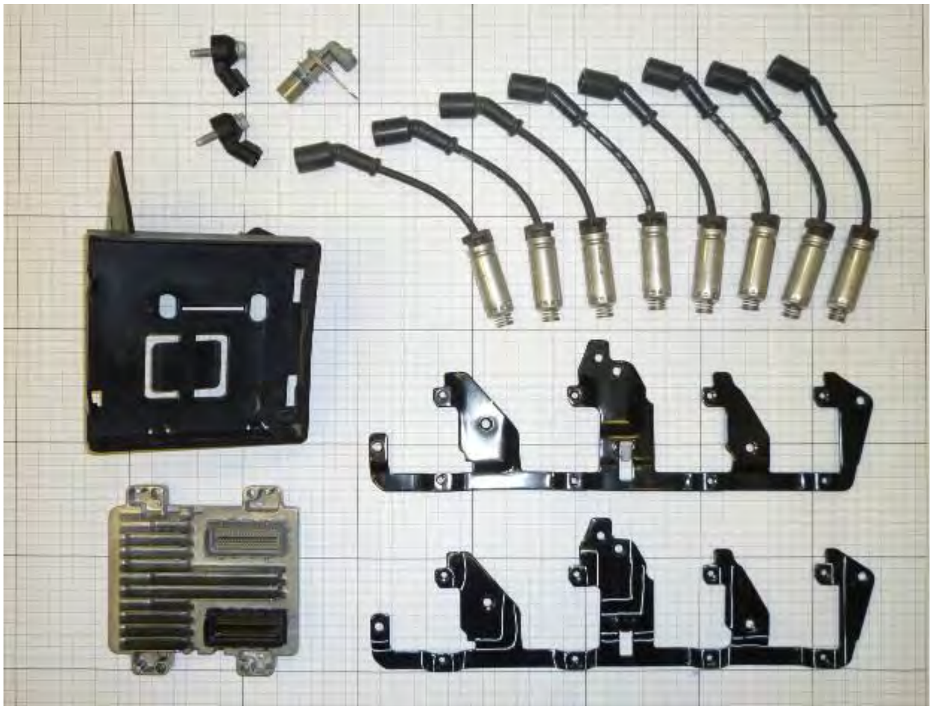


**Image 4.1-88: Engine Management, Electronic Subsystem Components**
*(Source: FEV, Inc.)*

### 4.1.16.3 Mass Reduction Industry Trends

The industry trend for lightweighting engine electronics is to use plastic for mounting whenever possible. Integrating mounting features on existing plastic components or designing plastic support brackets like the Silverado ECM bracket (**Image 4.1-89**).

### 4.1.16.4 Summary of Mass Reduction Concepts Considered

As shown in **Table 4.1-51**, the ECU Bracket Assembly and Spark Coil were considered for mass reduction.

**Table 4.1-51: Summary of Mass Reduction Concepts Considered for Engine Management, Electronic Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Coil Bracket | Steel to Plastic and integrated into valve cover | 75% mass reduction | NVH concern |

#### 4.1.16.5 Selection of Mass Reduction Ideas

**Table 4.1-52** summarizes the ideas selected for the Engine Management, Engine Electronic, Electrical Subsystem.

**Table 4.1-52: Mass Reduction Ideas Selected for Engine Management, Electronic Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **60** | **00** | **Engine Management, Engine Electronic, Electrical Subsystem** | |
| 01 | 60 | 01 | Spark Plugs, Glow Plugs | N/A |
| 01 | 60 | 02 | Engine Management Systems, Engine Electronic Systems | N/A |
| 01 | 60 | 03 | Engine Electrical Systems (including Wiring Harnesses, Earth Straps, Ignition Harness, Coils, Sockets) | Coil Bracket - Integrated into valve cover |
| 01 | 60 | 99 | Misc. | N/A |
| | | | | |

Silverado's ignition coils are mounted to a stamped steel bracket (**Image 4.1-89**), which then mounts to the valve cover. A weight saving alternative would be to integrate coil mounting features into the valve cover, creating a single plastic component. Valve covers are a proven application for plastic. Glass reinforced nylon was selected to achieve the strength required to support the mass intensive ignition coils. In addition, to ensure durability and meet NVH requirements special design consideration would be required to properly support the mass of the coils. An example of an integrated coil mount valve cover is the 2014LT1 (**Image 4.1-90**).

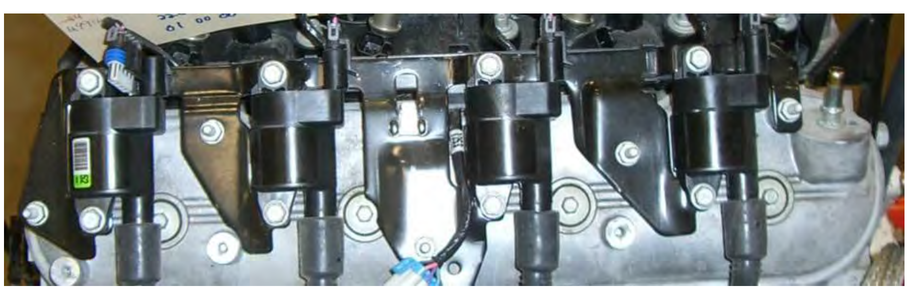


**Image 4.1-89: Silverado Coil Bracket**

*(Source: FEV, Inc.)*

**Image 4.1-90: 2014LT1 Integrated Coil Mount Valve Cover**
*(Source: http://wot.motortrend.com)*

#### 4.1.16.6 Mass Reduction and Cost Impact

As seen in **Table 4.1-53**, a metal-to-plastic integration applied to the coil bracket saves both mass and cost.

**Table 4.1-53: Mass Reduction and Cost Impact for Breather Subsystem**
*(See Appendix for Additional Cost Detail)*

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 01 | 60 | 00 | Engine Management, Engine Electronic, Electrical Subsystem | | | | | | |
| 01 | 60 | 01 | Spark Plugs, Glow Plugs | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 60 | 02 | Engine Management Systems, Engine Electronic Systems | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 60 | 05 | Engine Electrical Systems (including Wiring Harnesses, Earth Straps, Ignition Harness, Coils, Sockets) | A | 0.886 | $1.97 | $2.23 | 21.82% | 0.04% |
| 01 | 60 | 06 | Misc. | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | A | 0.886 (Decrease) | 1.973 (Decrease) | $2.23 (Decrease) | 15.63% | 0.04% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.1.17 Accessory Subsystems (Start Motor, Generator, etc.)

#### 4.1.17.1 Subsystem Content Overview

**Table 4.1-54** summarizes the mass breakdown for the Silverado engine accessories. The top mass contributors include the AC compressor and the alternator.

**Table 4.1-54: Mass Breakdown by Sub-subsystem for Accessory Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 01 | 70 | 00 | Accessory Subsystems (Start Motor, Generator, etc.) | |
| 01 | 70 | 01 | Starter Motors | 3.265 |
| 01 | 70 | 02 | Alternators | 6.699 |
| 01 | 70 | 03 | Power Steering Pumps | 0.000 |
| 01 | 70 | 04 | Vacuum Pumps | 0.000 |
| 01 | 70 | 05 | Air Conditioning Compressors | 6.244 |
| 01 | 70 | 06 | Hydraulic Pumps | 0.000 |
| 01 | 70 | 07 | Ventilator | 0.000 |
| 01 | 70 | 10 | Other Accessories | 0.000 |
| 01 | 70 | 99 | Misc. | 3.685 |
| | | | | |
| | | | Total Subsystem Mass = | 19.893 |
| | | | Total System Mass = | 239.945 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 8.29% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.81% |

### 4.1.17.2 Silverado Baseline Subsystem Technology

The Silverado Accessory Subsystem consists of the alternator, starter, AC compressor, AC bracket, and accessory bracket (**Image 4.1-91**).

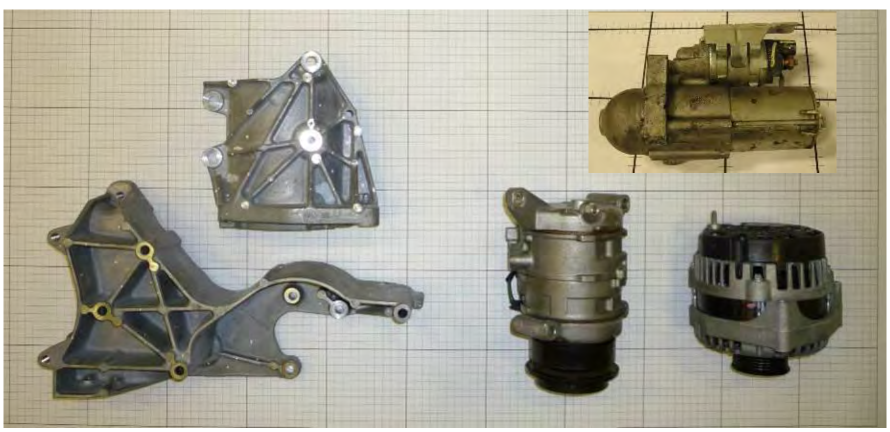


**Image 4.1-91: Accessory Subsystem Components**

*(Source: FEV, Inc.)*

#### 4.1.17.3 Mass Reduction Industry Trends

The trend for engine accessories is to remove them from the belt drive. Electrically driven devices can be powered to match accessory requirements savings power. In some cases, electrically driven systems can be lighter weight than standard belt driven accessories.

#### 4.1.17.4 Summary of Mass Reduction Concepts Considered

**Table 4.1-55** summarizes concepts considered for accessory lightweighting.

**Table 4.1-55: Summary of Mass Reduction Concepts Considered for Accessory Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Power Steering Pump | Cast Iron to Aluminum | 35% mass reduction | Improved heat dissipation |
| Air Cond. Bracket | Aluminum to Magnesium | 30% mass reduction | Coated fasteners required |
| Accessory Bracket | Aluminum to Magnesium | 30% mass reduction | Coated fasteners required |
| Accessory Bracket | Reduce size for Electric Power Steering | 40% mass reduction | Permits reduction in belt size and elimination of secondary AC belt |
| Accessory Bracket | Reduce size for EPS and Aluminum to Magnesium | 55% mass reduction | Coated fasteners required |

The power steering pump presents opportunity for significant mass savings by making the housing forged aluminum rather than cast iron. Electric power steering represents the future of steering systems. It was selected over hydraulic, eliminating this idea. Eliminating the hydraulic power steering pump enabled the elimination of the mounting feature from the accessory drive bracket which also facilitates alternator mounting.

#### 4.1.17.5 Selection of Mass Reduction Ideas

As seen in **Table 4.1-56**, the accessory bracket and AC compressor mounting bracket were selected for lightweighting.

**Table 4.1-56: Mass Reduction Ideas Selected for Accessory Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **01** | **70** | **00** | **Accessory Subsystems (Start Motor, Generator, etc.)** | |
| 01 | 70 | 01 | Starter Motors | N/A |
| 01 | 70 | 02 | Alternators | N/A |
| 01 | 70 | 03 | Power Steering Pumps | N/A |
| 01 | 70 | 04 | Vacuum Pumps | N/A |
| 01 | 70 | 05 | Air Conditioning Compressors | Compressor Bracket - Aluminum to Magnesium |
| 01 | 70 | 06 | Hydraulic Pumps | N/A |
| 01 | 70 | 07 | Ventilator | N/A |
| 01 | 70 | 10 | Other Accessories | N/A |
| 01 | 70 | 99 | Misc. | Accessory Bracket - remove PS mount<br>Accessory Bracket - Aluminum to Magnesium |
| | | | | |

The accessory mounting bracket found on Silverado (**Image 4.1-92**) was shortened for elimination of the hydraulic power steering pump (**Image 4.1-93**). This smaller bracket was also changed to magnesium along with the AC compressor bracket. Diecast magnesium brackets are in production (**Image 4.1-94** and **Image 4.1-95**) and easily manufactured.

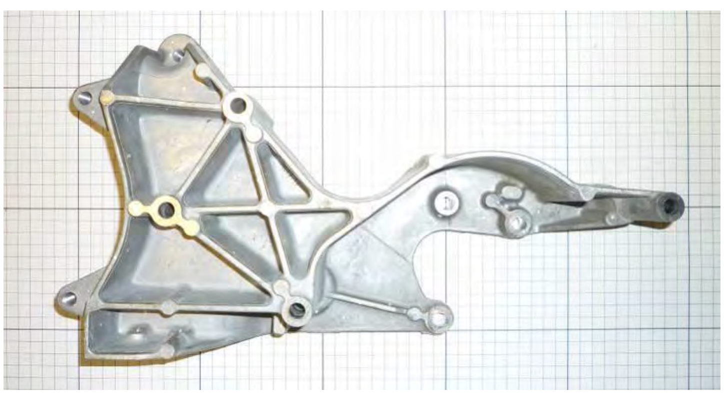
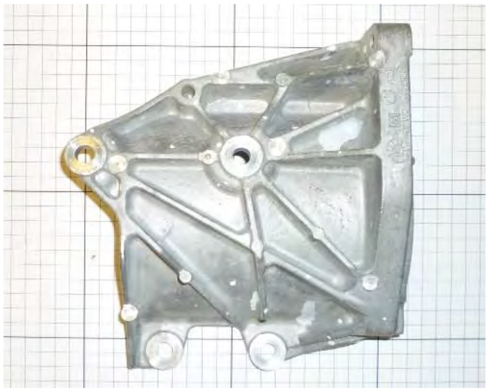


**Image 4.1-92 (Left): [Base Technology] Accessory Bracket**

**Image 4.1-93 (Right): [New Technology] Accessory Bracket w/o PS**

*(Source: FEV, Inc.)*



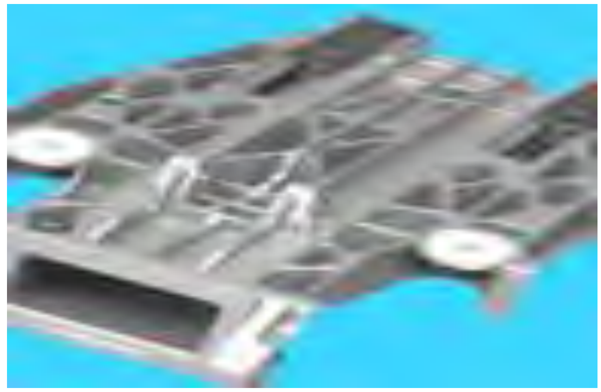


**Image 4.1-94 (Left): [Base Technology] AC Comp Bracket**
*(Source: slidegood.com)*

**Image 4.1-95 (Right): [New Technology] Steering Column Bracket**
*(Source: Meridian)*

### 4.1.17.6 Mass Reduction and Cost Impact

**Table 4.1-57** shows there is a cost increase for changing the AC Bracket material to magnesium. Cost for magnesium compatible fasteners was included.

**Table 4.1-57: Mass Reduction and Cost Impact for Accessory Subsystem**
*(See Appendix for Additional Cost Detail)*

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 01 | 70 | 00 | Accessory Subsystems (Start Motor, Generator, etc.) | | | | | | |
| 01 | 70 | 01 | Starter Motors | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 70 | 02 | Alternators | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 70 | 03 | Power Steering Pumps | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 70 | 04 | Vacuum Pumps | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 70 | 05 | Air Conditioning Compressors | X | 0.369 | -$2.42 | -$6.55 | 5.91% | 0.02% |
| 01 | 70 | 06 | Hydraulic Pumps | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 70 | 07 | Ventilator | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 70 | 10 | Other Accessories | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 01 | 70 | 99 | Misc. | A | 1.860 | $1.53 | $0.82 | 50.47% | 0.08% |
| | | | | B | 2.229 (Decrease) | -0.892 (Increase) | -$0.40 (Increase) | 11.20% | 0.09% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.1.18 Secondary Mass Reduction / Compounding

### 4.1.18.1 Subsystem Content Overview

Vehicle acceleration relates to vehicle mass. A lighter Silverado requires less power to achieve equal acceleration. The intent of investigating secondary mass savings is to quantify how much engine mass could be further reduced by reducing the vehicle mass.

Engine mass could also be reduced by performance enhancements like turbo charging. A turbo charged V6 is capable of producing the same power as Silverado's V8 and could save additional mass. Since performance enhancements like charge air systems, variable valve control, dual runner intakes, and others have been previously researched they were not evaluated in this investigation.

Silverado's 5.3L naturally aspirated engine produces 315 Hp resulting in 59.4 Hp/Liter. This output/liter was used to size the lightened Silverado engine.

To calculate the downsized power requirement (**Table 4.1-58**), base Silverado's gross vehicle weight rating (GVWR) was ratioed with a 20% curb weight reduction resulting in a 7% reduction in power. Maintaining the same power output per liter as the 5.3L LC9, results in a downsize displacement of 4.9 liters.

**Table 4.1-58: Downsized Engine Power Requirement Calculation**

| ENGINE SIZING | |
|---|---|
| **Silverado Curb Weight Reduction** | **20%** |
| Lightened Curb Weight (kgs) | 1963 |
| Lightened Weight (GCWR) | 6313 |
| Chevy Silverado Curb Weight (kgs) | 2454 |
| Gross Combination Weight Rating (GCWR) | 6804 |
| Power Reduction Factor | 0.928 |
| 5.3L Power (kW @5200) | 235 |
| 5.3L Torque (N*m @4000) | 454 |
| Reduced-Weight Power (kW) | 218 |
| Reduced-Weight Torque (N*m) | 421 |
| Vortech 5.3L Displacement (L) | 5.3 |
| **Downsized Displacement (L)** | **4.9** |

Displacement-driven engine components such as pistons, connecting rods, and engine block are directly sized by engine displacement. For these components downsized masses were estimated based on a 4.9L engine (**Table 4.1-59**). Secondary mass savings were derived from reduced component masses previously calculated for lightweighting technologies. All other components like those associated with the accessory and fasteners were not affected and masses unchanged. The result is 7.6 kg of additional mass savings based on downsizing.

**Table 4.1-59: Silverado Engine Downsizing Mass Savings by Component and Total**

| | Component | New Mass (kg) | Downsizing Approach | % Reduction | Length Reduction (mm) | Component Length (mm) | Compounded Mass Savings (kg) |
|---|---|---|---|---|---|---|---|
| 1 | Engine Mounts | 4.963 | Power Reduction | 7.0% | | | 0.348 |
| 2 | Crankshaft | 22.973 | Power Reduction | 7.0% | | | 1.611 |
| 3 | Connecting Rod | 3.584 | Power Reduction | 7.0% | | | 0.251 |
| 4 | Piston | 3.392 | Area Reduction | 7.3% | | | 0.249 |
| 5 | Engine Block | 43.695 | Power Reduction | 7.0% | | | 3.065 |
| 6 | Cylinder Head length | 22.618 | Block Length Reduction | 2.9% | 14.4 | 500 | 0.650 |
| 6 | Cylinder Head width | 21.968 | Deck Width Reduction | 2.4% | 3.6 | 150 | 0.526 |
| 7 | Valve Cover | 1.120 | Block Length Reduction | 3.0% | 14.4 | 480 | 0.034 |
| 8 | Camshaft | 3.491 | Block Length Reduction | 2.9% | 14.4 | 500 | 0.100 |
| 9 | Harmonic Balancer | 3.698 | Power Reduction | 7.0% | | | 0.259 |
| 10 | Oil Pan | 3.949 | Block Length Reduction | 2.6% | 14.4 | 560 | 0.101 |
| 11 | Windage Plate | 0.369 | Block Length Reduction | 3.1% | 14.4 | 470 | 0.011 |
| 12 | Radiator | 5.684 | Power Reduction | 7.0% | | | 0.399 |
| | Total (kg) | 141.504 | | | | | **7.605** |

Material savings for compounded components was totaled to estimate the cost impact of downsizing. Labor and burden costs were considered unchanged.

**Table 4.1-60** details mass and cost impact of compounding. These figures are based on downsizing the already lightweighted concept as outlined in previous sections. The table also includes data for new technology which saved 23.8kg. The total mass reduction achieved for the Engine System including compounding is 31.8 kg.

**Table 4.1-60: Mass Reduction and Cost Impact for Engine System Secondary Mass Savings**

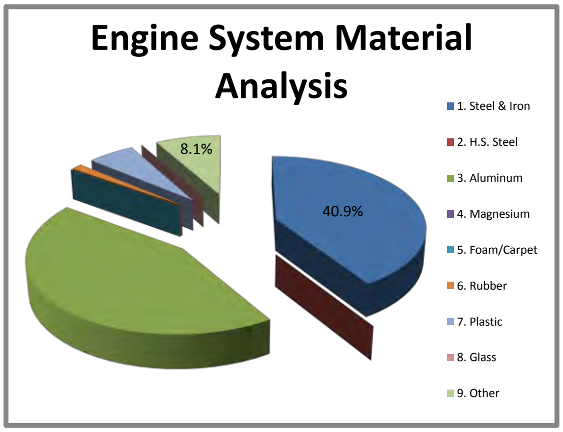
| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 01 | 00 | 00 | Engine System | | | | | | | | |
| 01 | 02 | 00 | Engine Frames, Mounting, and Brackets Subsystem | 1.10 | 0.348 | 1.45 | -$0.01 | $0.58 | $0.57 | $0.39 | 0.1% |
| 01 | 03 | 00 | Crank Drive Subsystem | 2.38 | 2.11 | 4.49 | $2.95 | $4.10 | $7.05 | $1.57 | 0.2% |
| 01 | 04 | 00 | Counter Balance Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 05 | 00 | Cylinder Block Subsystem | 3.30 | 3.07 | 6.36 | $0.80 | $9.35 | $10.15 | $1.60 | 0.3% |
| 01 | 06 | 00 | Cylinder Head Subsystem | 1.16 | 1.21 | 2.37 | $6.06 | $3.69 | $9.75 | $4.11 | 0.1% |
| 01 | 07 | 00 | Valvetrain Subsystem | 0.192 | 0.126 | 0.318 | $0.05 | $0.45 | $0.50 | $1.57 | 0.0% |
| 01 | 08 | 00 | Timing Drive Subsystem | 0.415 | 0.00 | 0.415 | -$2.44 | $0.00 | -$2.44 | -$5.88 | 0.0% |
| 01 | 09 | 00 | Accessory Drive Subsystem | 1.73 | 0.325 | 2.06 | $0.73 | $0.00 | $0.73 | $0.35 | 0.1% |
| 01 | 10 | 00 | Air Intake Subsystem | 0.941 | 0.00 | 0.941 | -$0.54 | $0.00 | -$0.54 | -$0.58 | 0.0% |
| 01 | 11 | 00 | Fuel Induction Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 12 | 00 | Exhaust Subsystem | 3.15 | 0.28 | 3.43 | -$20.00 | $0.97 | -$19.03 | -$5.56 | 0.1% |
| 01 | 13 | 00 | Lubrication Subsystem | 3.01 | 0.112 | 3.12 | -$11.24 | $0.55 | -$10.69 | -$3.42 | 0.1% |
| 01 | 14 | 00 | Cooling Subsystem | 3.31 | 0.457 | 3.77 | -$92.06 | $2.11 | -$89.95 | -$23.85 | 0.2% |
| 01 | 15 | 00 | Induction Air Charging Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 16 | 00 | Exhaust Gas Re-circulation Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 17 | 00 | Breather Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.0% |
| 01 | 60 | 00 | Engine Management, Engine Electronic, Electrical Subsystem | 0.886 | 0.00 | 0.886 | $1.97 | $0.00 | $1.97 | $2.23 | 0.0% |
| 01 | 70 | 00 | Accessory Subsystems (Start Motor, Generator, etc.) | 2.23 | 0.00 | 2.23 | -$0.89 | $0.00 | -$0.89 | -$0.40 | 0.1% |
| | | | | 23.8 (Decrease) | 8.0 (Decrease) | 31.8 (Decrease) | -$114.63 (Increase) | $21.81 (Decrease) | -$92.83 (Increase) | -$2.92 (Increase) | 1.30% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.1.19 Engine System Material Analysis

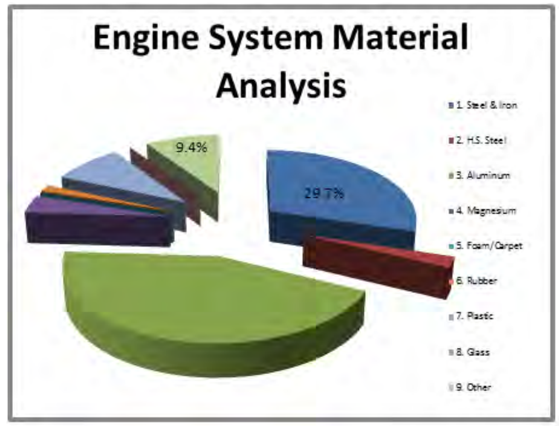
A material breakdown for the base Engine System and for the baseline and compounded Engine System is provided in **Figure 4.1-2.** The "Steel & Iron" content category was reduced by more than 11%, while "Plastic" increased by 3.2%. Magnesium content increased from 0% to 4.1%. Aluminum content remained unchanged.

**Baseline Engine System**




| | | Material Categories: |
|---|---|---|
| 40.9% | 98.211 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 43.9% | 105.330 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 1.3% | 3.126 | 6. Rubber |
| 5.8% | 13.892 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 8.1% | 19.385 | 9. Other |
| 100% | 239.945 | TOTAL |

**Total Engine System**




| | | Material Categories: |
|---|---|---|
| 29.7% | 61.789 | 1. Steel & Iron |
| 2.4% | 5.018 | 2. H.S. Steel |
| 43.9% | 91.265 | 3. Aluminum |
| 4.0% | 8.403 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 1.5% | 3.197 | 6. Rubber |
| 9.0% | 18.798 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 9.4% | 19.638 | 9. Other |
| 100% | 208.108 | TOTAL |

**Figure 4.1-2: Calculated Engine System Baseline Material and Total Material Content**

## 4.2 Transmission

The Chevrolet Silverado 6L80E transmission package, as shown in **Image 4.2-1**, is a six-speed automatic transmission built by General Motors at its Toledo Transmission Plant (TTO). Introduced in late 2005, it is very similar in design to the smaller 6L45/6L50, produced at GM Powertrain in Strasbourg, France. It features clutch-to-clutch shifting, eliminating the one-way clutches used on older transmission designs. Some weight-reduction concepts were used when it was designed, but durability and reliability were foremost in the design process.

GM has announced that TTO will produce a new eight-speed transmission at its facility. This new GM-designed transmission will be used in several models by the end of 2016, the automaker has said. This is not the TL80 eight-speed automatic that will be used in the redesigned 2014 Cadillac CTS, Aisin will supply that transmission. GM is spending $55.7 million on its transmission plant in Toledo, and $29.4 million on its casting plant in Bedford, Ind., for its new eight-speed transmission. It is our understanding that this new transmission is an upgrade of the 6L80 traditional style for use in the pickup, SUV trucks, and Corvette presumed to be available for 2014. You would assume that during the design of this new system that some of today's light weighting techniques will prevail through the project.

The joint venture GM has entered into with Ford has promised to bring a 9- and 10-speed to the marketplace. The intention of this project is to develop a nine-speed transmission for front-wheel drive vehicles and a more robust 10 speed for rear wheel drive pickup trucks and SUVs. The targeted launch date for these was to be 2016, but the idea of whether all this transmission development can be accomplished in this timeframe (even with both companies putting their resources together) is considerable.

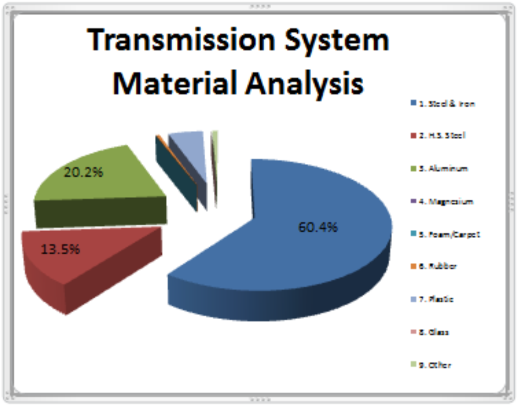
Understanding that the package envelops for these transmission is not getting bigger and that everyday weight restrictions are driven into every system design groups arena the new materials and strength increasing processes that have been suggested in the Silverado 6 speed will be considered and embraced.

As shown in **Table 4.2-1**Error! Reference source not found., there are key areas in the unit for mass reduction opportunities.

**Image 4.2-1: General Motors 6L80e Automatic Transmission**
*(Source: Queensland.com)*

**Table 4.2-1: Baseline Subsystem Breakdown for Transmission System**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 02 | 00 | 00 | Transmission System | |
| 02 | 01 | 00 | External Components | 0.023 |
| 02 | 02 | 00 | Case Subsystem | 30.725 |
| 02 | 03 | 00 | Gear Train Subsystem | 12.392 |
| 02 | 04 | 00 | Internal Clutch Subsystem | 30.469 |
| 02 | 05 | 00 | Launch Clutch Subsystem | 20.290 |
| 02 | 06 | 00 | Oil Pump and Filter Subsystem | 7.496 |
| 02 | 07 | 00 | Mechanical Controls Subsystem | 7.138 |
| 02 | 08 | 00 | Electrical Controls Subsystem | 4.299 |
| 02 | 09 | 00 | Parking Mechanism Subsystem | 0.876 |
| 02 | 10 | 00 | Misc. Subsystem | 0.000 |
| 02 | 11 | 00 | Electric Motor & Controls Subsystem | 0.000 |
| 02 | 12 | 00 | Transfer Case Subsystem | 28.439 |
| 02 | 20 | 00 | Driver Operated External Controls Subsystem | 3.130 |
| | | | | |
| | | | **Total System Mass=** | 145.276 |
| | | | **Total Vehicle Mass=** | 2454 |
| | | | **System Mass Contribution Relative to Vehicle=** | 5.92% |




| | | Material Categories: |
|---|---|---|
| 60.4% | 87.748 | 1. Steel & Iron |
| 13.5% | 19.592 | 2. H.S. Steel |
| 20.2% | 29.301 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.5% | 0.681 | 6. Rubber |
| 4.8% | 6.945 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.7% | 1.010 | 9. Other |
| 100% | 145.276 | TOTAL |

**Figure 4.2-1: Transmission System Base Material Content**

As shown in **Table 4.2-2**, there are material, technological, and process mass reduction opportunities that are available for future transmissions.

**Table 4.2-2: Mass reduction and Cost Impact for Transmission System**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | System/ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | 2454 | | | | | | |
| 02 | 00 | 00 | **Transmission System** | | | | | | |
| 02 | 01 | 00 | External Components | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 02 | 00 | Case Subsystem | | 10.659 | -$30.60 | -$2.87 | 34.69% | 0.43% |
| 02 | 03 | 00 | Gear Train Subsystem | | 2.052 | $24.18 | $11.79 | 16.56% | 0.08% |
| 02 | 04 | 00 | Internal Clutch Subsystem | | 4.232 | -$39.94 | -$9.44 | 13.89% | 0.17% |
| 02 | 05 | 00 | Launch Clutch Subsystem | | 8.622 | -$21.73 | -$2.52 | 42.49% | 0.35% |
| 02 | 06 | 00 | Oil Pump and Filter Subsystem | | 2.419 | -$11.52 | -$4.76 | 32.27% | 0.10% |
| 02 | 07 | 00 | Mechanical Controls Subsystem | | 0.872 | -$5.03 | -$5.76 | 12.22% | 0.04% |
| 02 | 08 | 00 | Electrical Controls Subsystem | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 09 | 00 | Parking Mechanism Subsystem | | 0.060 | $5.24 | $87.45 | 6.84% | 0.00% |
| 02 | 10 | 00 | Misc. Subsystem | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 11 | 00 | Electric Motor & Controls Subsystem | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 12 | 00 | Transfer Case Subsystem | | 5.271 | -$48.81 | -$9.26 | 18.53% | 0.21% |
| 02 | 20 | 00 | Driver Operated External Controls Subsystem | | 0.000 | $0.00 | -- | -- | 0.00% |
| | | | | X | 34.186 (Decrease) | -$128.20 (Increase) | -$3.75 (Increase) | 23.53% | 1.39% |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.2.1 External Components Subsystem

### 4.2.1.1 Subsystem Content Overview

After a systematic investigation, no opportunities for mass reduction or cost benefits were found in this subsystem (as shown in **Table 4.2-3**).

**Table 4.2-3: Mass Breakdown by Sub-subsystem for External Components**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 01 | 00 | **External Components** | |
| 02 | 01 | 01 | Lifting Hooks / Eyes | 0.000 |
| 02 | 01 | 02 | Venting Caps (Transmission Breather) | 0.023 |
| 02 | 01 | 99 | Misc. | 0.000 |
| | | | | |
| | | | **Total Subsystem Mass =** | **0.023** |
| | | | **Total System Mass =** | **145.276** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **0.02%** |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | **0.00%** |

## 4.2.2 Case Subsystem

### 4.2.2.1 Subsystem Content Overview

As shown in **Table 4.2-4,** the most significant contributor to the mass reduction of the Case Subsystem was the raw material in the case components. The Case Subsystem is made up of three sections (**Image 4.2-2**): the bell housing, transmission, and transfer case. These sections are currently made of aluminum SAE 380 alloy.

**Image 4.2-2: Case Subsystem Housings**
*(Source: FEV, Inc.)*

**Table 4.2-4: Mass Breakdown by Sub-subsystem for Cass Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 02 | 00 | Case Subsystem | |
| 02 | 02 | 01 | Tranmission Case | 18.784 |
| 02 | 02 | 02 | Transfer Housing | 10.092 |
| 02 | 02 | 03 | Covers | 0.037 |
| 02 | 02 | 04 | Transmission Fluid measurement | 0.363 |
| 02 | 02 | 05 | Bolts | 1.304 |
| 02 | 02 | 99 | Misc. | 0.145 |
| | | | | |
| | | | Total Subsystem Mass = | 30.725 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 21.15% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.25% |

### 4.2.2.2 Chevrolet Silverado Baseline Subsystem Technology

For years, Chevrolet has used aluminum transmission cases and optimized its thin wall casting procedure. The strength and integrity of its cases have never proposed an issue or concern; its mass weight compares to others in the industry using aluminum.

#### 4.2.2.3 Mass reduction Industry Trends

There are manufacturers in the industry that have adopted the use of alternate materials such as magnesium alloy in order to reduce transmission weight and still maintain case integrity. Among these manufacturers is Mercedes-Benz with its seven-speed transmission, the 7G-TRONIC. General Motors annually produces approximately 1 million GMT800 full-size trucks and SUVs that have two magnesium transfer case halves with a total weight of 7 kg per unit. Volkswagen produces daily 600 magnesium alloy manual transmission cases for its Passat and the Audi A4/A6. The magnesium transmission case is a proven mass reduction product.

Carbon fiber combinations have also been found as alternate materials for transmission cases. Composite gearboxes are significantly lighter than traditional alloy boxes, have up to 25% more stiffness, can operate at higher temperatures, and are easy to modify and repair. Carbon fiber composites now make up almost 85% of the volume of a contemporary Formula 1 car while accounting for less than 25% of its mass (such as the one shown in **Image 4.2-3**).

**Image 4.2-3: 2004 Bar Honda Team Composite Gearbox**
*(Source: Honda Formula 1 photo)*

Along with the obvious weight savings, composite gearboxes have almost infinite fatigue durability and thusly can be made far more cost effective than the alloy boxes which they replace. At this time, however, there are no viable manufacturing processes that can manufacture a transmission case in the time required for mass production.

#### 4.2.2.4 Summary of Mass reduction Concepts Considered

**Table 4.2-5** shows the mass reduction ideas considered for the Case Subsystem. Chevrolet has always been mass reduction conscious in its designs, but tends to lean toward the conservative and cost-conscious side of the engineering spectrum in drive train design. This is why carbon fiber and magnesium have not found their way into the Silverado's drive train components.

**Table 4.2-5: Summary of Mass reduction Concepts Initially Considered for Transmission Case Subassembly**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Aluminum Case Assemble | Reduce wall thickness | 10% weight save | Integrity and strength compromised |
| Aluminum Case Assemble | Carbon fiber material replacement | 50% weight save | Extensive engineering hurdles to overcome |
| Aluminum Case Assemble | Magnesium material replacement | 30% weight save | Low risk moderate cost increase |

#### 4.2.2.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected from this subassembly are shown below in **Table 4.2-6**. Components shown utilizing magnesium alloy will meet the integrity needs of the system and fulfill the mass reduction parameters.

**Table 4.2-6: Mass reduction Ideas Selected for Detail Case Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 02 | 02 | 00 | **Case Subsystem** | |
| 02 | 02 | 01 | Tranmission Case | Replace a 390 aluminum casting with Mg |
| 02 | 02 | 02 | Transfer Housing | Replace a 390 aluminum casting with Mg |
| 02 | 02 | 03 | Covers | Replace a 390 aluminum casting with Mg |
| 02 | 02 | 04 | Transmission Fluid measurement | n/a |
| 02 | 02 | 05 | Bolts | n/a |
| 02 | 02 | 99 | Misc. | n/a |

#### 4.2.2.6 Mass reduction and Cost Impact

The greatest mass reduction was gained by the material selection of magnesium alloy, as shown in **Table 4.2-7**. Analysis of the thin wall on each of the components of the subassembly did not garner an outcome that would have proven to be an advantage to the end product. Although there were opportunities to reduce the actual mass of the Case Subsystem, those have not pursued them at this time. The choice of magnesium has been proven to be cost-effective and meet the mass reduction goals.

**Table 4.2-7: Subsystem Mass Reduction and Cost Impact Estimates for Case Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 02 | 02 | 00 | Case Subsystem | | | | | | |
| 02 | 02 | 01 | Tranmission Case | | 6.934 | -$21.38 | -$3.08 | 36.91% | 0.28% |
| 02 | 02 | 02 | Transfer Housing | | 3.408 | -$4.50 | -$1.32 | 33.77% | 0.14% |
| 02 | 02 | 03 | Covers | | 0.014 | -$0.13 | -$9.51 | 37.84% | 0.00% |
| 02 | 02 | 04 | Transmission Fluid measurement | | 0.303 | -$1.07 | -$3.52 | 83.47% | 0.01% |
| 02 | 02 | 05 | Bolts | | 0.000 | -$3.53 | -- | -- | 0.00% |
| 02 | 02 | 99 | Misc. | | 0.000 | $0.00 | -- | -- | 0.00% |
| | | | | 1C | 10.659 (Decrease) | -$30.60 (Increase) | -2.871 (Increase) | 34.69% | 0.43% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.2.3 Gear Train Subsystem

#### 4.2.3.1 Subsystem Content Overview

As shown in **Table 4.2-8**, the gear train offered opportunities to reduce weight and lower cost for the transmission. We will look outside of the auto industry for ideas to shed weight.

**Table 4.2-8: Mass Breakdown by Sub-subsystem for Gear Train Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 03 | 00 | Gear Train Subsystem | |
| 02 | 03 | 01 | Sun Gears | 1.114 |
| 02 | 03 | 02 | Ring Gears | 3.140 |
| 02 | 03 | 03 | Planetary Gears | 2.033 |
| 02 | 03 | 04 | Planetary Carriers | 4.637 |
| 02 | 03 | 05 | Bearings | 1.019 |
| 02 | 03 | 99 | Misc. | 0.450 |
| | | | | |
| | | | Total Subsystem Mass = | 12.392 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 8.53% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.50% |

### 4.2.3.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet 6L80E transmission Gear Train Subsystem is a very robust second-generation unit: the "6" in 6L80E denotes the number of forward speeds, while "80" is an arbitrary figure that represents its strength. The 6L80E replaced the venerable, first-generation TH400-based 4L80E (rather than some view as succeeding the 700R4-based 4L60E). GM's 6-speed has been reserved for only the most demanding applications, such as those in fifth-generation Camaros, C6 Corvettes, and heavy-duty trucks and SUVs.

### 4.2.3.3 Mass reduction Industry Trends

The gear train has opportunities for cost-effective light-weighting as well as longer life cycles through the use of aerospace-style lightened gear designs and raw materials. New and smaller plastic components will be used to reduce weight and cost throughout the overall mass of the transmission. Today, the actual transmission is becoming more compact and gear selection is getting larger.

#### 4.2.3.4 Summary of Mass reduction Concepts Considered

**Table 4.2-9** shows the mass reduction ideas considered for the 6L80E Gear Train Subsystem. The present Chevrolet gear train design is compact and demonstrates a conscious engineering design choice toward durability.

**Table 4.2-9: Summary of Mass reduction Concepts Initially Considered for Gear Train Subassembly**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Sun, Ring & Planet Gears | Replace 8620 & 4140 Gear Steel with C 61, C64, M53, 9310 and 6265 | 10 to 25% weight save | No risk moderate cost increase |
| PM Sintered Carrier | Replace PM with Schaeffler design 4130 Stamped Steel | 30% weight save | Engineered solution dependent some risk |
| Steel Thrust Bearings | Replace steel with Vespel Sp-21D | 75% weight save | Low risk cost save |

The light-weighting techniques used to downsize drive train gears in an automotive transmission are the same as those used by aerospace gear box designers. A mindset during the design process that utilizes all materials and process advantages available allows for an outcome that will meet the end user’s needs and requirements. Today’s design and simulation tools allow ideas to now be designed, tested, and examined within the same day rather than what previously required weeks or months. These tools allow lighter, stronger, and better transmissions to be designed for the future.

Aerospace gear material, such as C61, C64, Pyrowear® 53 (from QuesTek Innovations), and other 6265 products provide the ability to reduce the drive gear mass in this system. These new alloys provide three different levels of case hardness (with the ability to “dial-in” hardness profiles, including exceptionally high case hardness). Their high core strength, toughness, and other properties also offer the potential to reduce drivetrain weight or increase power density relative to incumbent alloys such as AISI 9310 or Pyrowear® Alloy 53. This new class of alloys utilizes an efficient nanoscale M2C carbide strengthening dispersion. Key benefits of these alloys include: high fatigue resistance (in contact, bending, and scoring); high hardenability achieved via low-pressure carburization (thus reducing quench distortion and associated manufacturing steps); a tempering temperature of 900°F or higher (providing up to a 500°F increase in thermal stability relative to incumbent alloys); and core tensile strengths in excess of 225 ksi.

**Table 4.2-10**: **Gear Material Density, Cost (2013 CY), and Weight Reduction**

| | Gear Steel Today | | | |
|---|---|---|---|---|
| | AISI Grade | Density kg/m* | $ per Kg | Weight Reduction % |
| Standard | 1030 | 7.7 t0 8.5 | 1.3 | 0.00% |
| | 1080 | 7.7 t0 8.5 | 1.56 | 0.00% |
| | 4118 | 7.7 t0 8.5 | 2.07 | 0.00% |
| | 4140 | 7.7 t0 8.5 | 1.72 | 0.00% |
| High Strength | 4320 | 7.7 t0 8.5 | 4.12 | 3.00% |
| | 4620 | 7.7 t0 8.5 | 3.39 | 3.00% |
| | 5140 | 7.7 t0 8.5 | 1.35 | 5.00% |
| | 6265 | 7.7 t0 8.5 | 1.75 | 7.00% |
| | 8620 | 7.7 t0 8.5 | 1.92 | 8.00% |
| | 9310 | 7.7 t0 8.5 | 3.34 | 10.00% |
| Aerospace | Pyro 53 | 7.7 t0 8.5 | 5.5 | 13.00% |
| | C61 | 7.7 t0 8.5 | 44.09 | 20.00% |
| | C64 | 7.7 t0 8.5 | 39.68 | 20.00% |

With selective use of these materials, the sun, ring, and planet gears' finish, durability, life cycle, and processing costs can be improved. The current cost of these technically advanced materials will limit their use in the near-term; however, by 2025 it is anticipated that the cost of these materials will be competative in relation to current top performing materials like 9310 and Pyro 53 providing viable alternatives to achieving weight reduction (**Table 4.2-10**). Some automotive companies are currently using these materials for gears that are in need of integrity help in their application. Premium material is used as much as possible within the parameters of this study. For the analysis FEV assumed the cost of C61 at $5.50/kg and C64 at $3.84/kg.

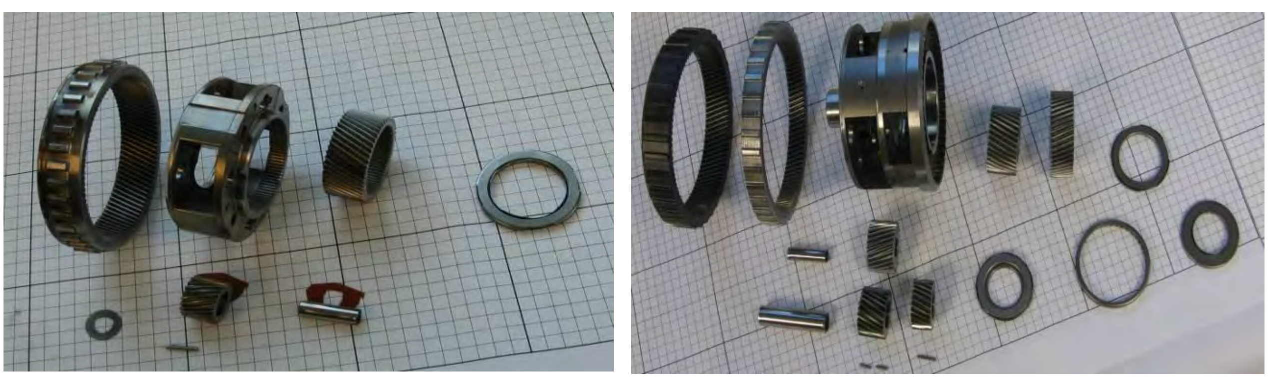


**Image 4.2-4: Gear Train Subsystem**
*(Source: FEV, Inc.)*

Replacing the powder metal sintered carrier with a lightweight stamped steel design (**Image 4.2-5**) proved to be a significant weight savings in the planet carrier. The cost was not prohibitive after investigation. There are many vehicles in the field that utilize this configuration for weight savings in their differential applications. INA's light-weight spur gear differential can weigh 30% less than a traditional bevel gear carrier and remain completely inside the original design envelope. This is a tremendous improvement in the power density of a differential. INA's spur gear differential offers distinct advantages over a bevel gear arrangement:

• Reduced $CO_2$ emissions with its lighter weight

• Much more compact than a conventional bevel gear differential

• Higher torque capacity despite its lower weight

• Custom designed for each transmission application

Different gearing variations allow Scheaffler to custom design a spur gear differential to fit the application. Four technically viable gearing concepts allow different designs to keep costs low and make the best use of space in the case. This is just the first step in weight reduction: for customers, transmission cases can be smaller, lighter, and less expensive.

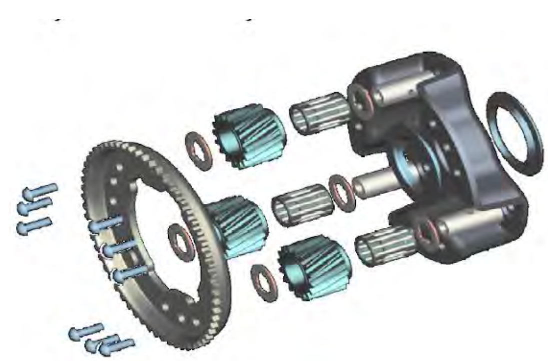


**Image 4.2-5: Planet Carrier Sub-Subsystem**
*(Source: GKN & INA photos)*

DuPont™ Vespel® SP-21 replaced the industry standard steel thrust bearings. Considered among other products, Vespel had all the qualities required for a worry-free replacement in our application; it has a proven track record of success in other transmissions.

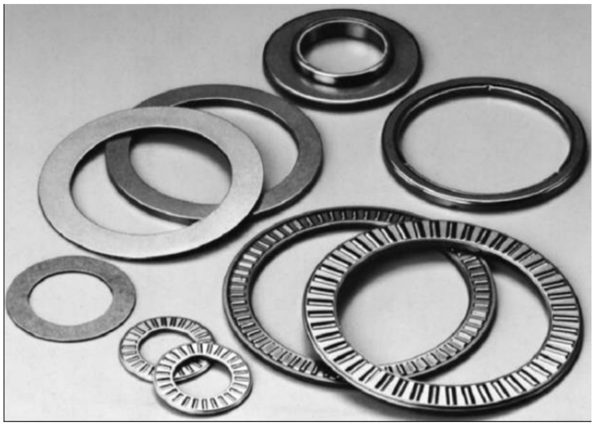


**Image 4.2-6: Thrust Bearing**
*(Sources: Timken and DuPont photos)*

### 4.2.3.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected from this subassembly are shown below **Table 4.2-11**.

The gear system configuration was lightened by using high-strength C61 and C64 aerospace steel alloys to ensure the subassembly integrity. Next is the planetary carrier, which will be a stamped steel assembly with spur gears. Finally, the thrust bearings shown in **Image 4.2-6** utilized Vespel SP-21D, which, as mentioned previously, is a DuPont product in use by many other transmission builders.

**Table 4.2-11: Mass reduction Ideas Selected for Gear Train Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| **02** | **03** | **00** | **Gear Train Subsystem** | |
| 02 | 03 | 01 | Sun Gears | Replace 4130 with C61 |
| 02 | 03 | 02 | Ring Gears | Replace 4140 with C64 |
| 02 | 03 | 03 | Planetary Gears | Replace 4320 with C64 |
| 02 | 03 | 04 | Planetary Carriers | Powder Metal to Stamped Steel |
| 02 | 03 | 05 | Bearings & Pins | Steel Bearings to Vespel |
| 02 | 03 | 99 | Misc. | n/a |

#### 4.2.3.6 Mass reduction and Cost Impact Estimates

Using aerospace gear lighting techniques and materials as on all of the gears and shafts in an automotive transmission should be the norm

Table **4.2-12**).

Stamped steel instead of cast iron on the differential carrier is a 30% weight savings with a cost that is well within the realm of reason for this large weight loss.

The mass reductions in this subsystem were gained by the material selection and gear lightening techniques. The selection of Vespel® reduced the bearings' cost by 60% to 70%, with a weight loss per bearing of more than 75%.

**Table 4.2-12: Subsystem Mass Reduction and Cost Impact for Case Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 02 | 03 | 00 | Gear Train Subsystem | | | | | | |
| 02 | 03 | 01 | Sun Gears | | 0.167 | -$3.11 | -$18.59 | 15.00% | 0.01% |
| 02 | 03 | 02 | Ring Gears | | 0.471 | -$5.75 | -$12.21 | 15.00% | 0.02% |
| 02 | 03 | 03 | Planetary Gears | | 0.305 | $5.85 | $19.18 | 15.00% | 0.01% |
| 02 | 03 | 04 | Planetary Carriers | | 0.695 | $4.13 | $5.94 | 14.99% | 0.03% |
| 02 | 03 | 05 | Bearings | | 0.045 | $23.06 | $518.13 | 4.37% | 0.00% |
| 02 | 03 | 99 | Misc. | | 0.369 | $0.00 | $0.00 | 82.00% | 0.02% |
| | | | | X | 2.052 (Decrease) | $24.18 (Increase) | 11.785 (Increase) | 16.56% | 0.08% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.2.4 Internal Clutch Subsystem

#### 4.2.4.1 Subsystem Content Overview

After a systematic examination, opportunities were found for both mass reduction or cost benefits in this subsystem. As seen in **Table 4.2-13**, the most significant contributor to the mass of the Internal Clutch Subsystem is the clutch and brake hubs (**Image 4.2-7**).

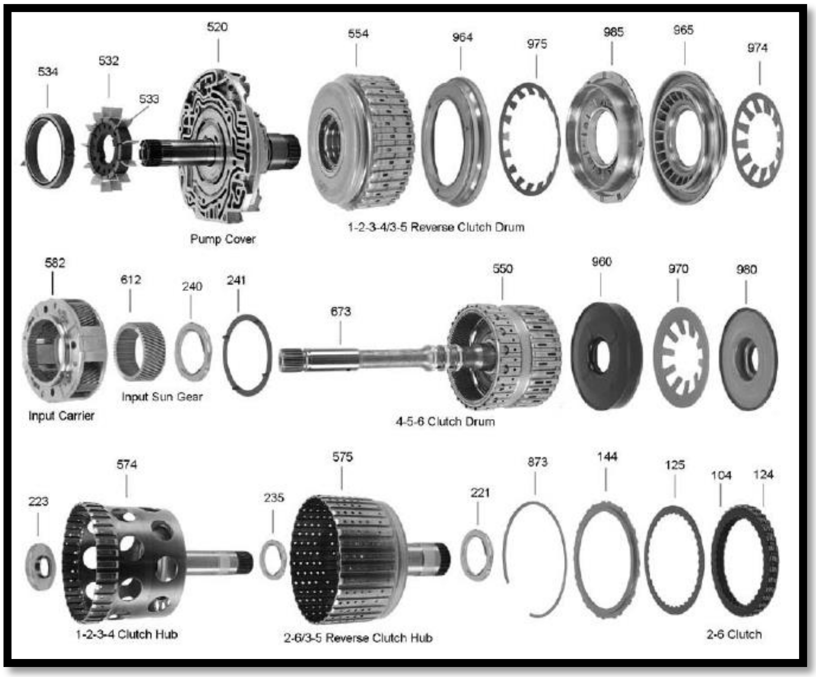



**Image 4.2-7: Internal Clutch Subsystem**
*(Source: ATSG photos)*

**Table 4.2-13: Mass Breakdown by Sub-subsystem for Internal Clutch**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 04 | 00 | Internal Clutch Subsystem | |
| 02 | 04 | 01 | Sprague / One-Way Clutches | 2.237 |
| 02 | 04 | 02 | Brake & Clutch Asm | 0.000 |
| 02 | 04 | 03 | Clutch & Brake Hubs | 20.715 |
| 02 | 04 | 04 | Shafts, Sleeves & Couplers | 0.000 |
| 02 | 04 | 05 | Clutch & Brake Discs & Plates | 6.931 |
| 02 | 04 | 99 | Misc. | 0.586 |
| | | | | |
| | | | Total Subsystem Mass = | 30.469 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 20.97% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.24% |

### 4.2.4.2 Chevrolet Silverado Baseline Subsystem Technology

The Internal Clutch System in the GM 6L80E transmission has no bands – only clutches – and heavily relies on electronics for all aspects of operation. By eliminating the bands, GM reduced the number of torque-handling components inside the transmission while also improving shift quality. The 6L80E is a clutch-to-clutch unit, which means that unless one clutch engages at exactly the same time when another clutch is disengaging, the transmission will bind up. When GM factory-assembles the 6L80E, it installs a control module directly to the valve body. It houses all the pressure control solenoids, shift solenoids, and the transmission control module in one sealed unit. There are many electronic adjustments that can be made to alter clutch pressures and apply times for durability. The factory tuning is good and manages the shift quality well.

### 4.2.4.3 Mass Reduction Industry Trend

More gears and a more complex gear selection mean more efficient internal clutch system demands. Material selection and mass reduction were the only opportunities found in this subsystem. We have concentrated on the material for the clutch drums that will allow system mass reduction while still ensuring the same integrity.

### 4.2.4.4 Summary of Mass Reduction Concepts Considered

**Table 4.2-14** shows the mass reduction ideas considered for the Internal Clutch Subsystem. The subsystem has a one-way sprag clutch in it. The clutch hub material presented opportunities to reduce mass. Material choice for mass reduction was dictated by the maintenance of product performance and integrity.

**Table 4.2-14: Summary of Mass Reduction Ideas Considered for Internal Clutch Subsystem**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Sprague / One-Way Clutches | Replace 8620 & 4140 Gear Steel with C 61, C64, M53, 9310 and 6265 | 10 to 25% weight save | No risk moderate cost increase |
| Clutch & Brake Hubs | Replace mild steel drum with high strength steel with thiner wall | 10% weight save | Engineered solution dependent some risk |
| Steel Thrust Bearings | Replace steel with Vespel Sp-21D | 75% weight save | Low risk cost save |

#### 4.2.4.5 Selection of Mass Reduction Ideas

The mass reduction ideas for this subsystem are shown here in **Table 4.2-15**.

**Table 4.2-15: Mass reduction Ideas Selected for Internal Clutch Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 02 | 04 | 00 | **Internal Clutch Subsystem** | |
| 02 | 04 | 01 | Spraque | Replaced Powder Metal with C61 |
| 02 | 04 | 02 | Brake & Clutch Assembly | n/a |
| 02 | 04 | 03 | Clutch & Brake Hubs | Replaced 4140 & PM with C61 and MMC |
| 02 | 04 | 04 | Shafts, Sleeves & Couplings | n/a |
| 02 | 04 | 05 | Clutch & Bake Discs/Plates | n/a |
| 02 | 04 | 99 | Misc, | Replaced Molded Ruber with TPS |

Having had conversation with the bearing and sprag clutch manufactures about these products (**Image 4.2-8**) that are supplied to the OEMs, they say that lighter and more effective clutches are in development. A functional and robust bi-directional sprag clutch would be a great opportunity to improve the functionality of the transmission and reduce mass. With time, a 10% weight savings on the present sprag unit can be realized.

**Image 4.2-8: Sprag Clutch Assembly**
*(Source: FEV, Inc.)*

In the Internal Clutch Subsystem, an opportunity to shed some weight was found within the high-strength steel drums. Today's plates are drawn into a cup, and then the side wall of the cup is formed into a gear shape by ironing, as shown in **Image 4.2-9**.


**Image 4.2-9: Gear Drum Formed by Ironing Side Wall of Cup**
*(Source: FEV, Inc.)*

Forging from billets as an option is inappropriate to the production of parts having little thickness (such as gear drums) due to the large change in shape. Thus, the application of bulk forming from plates having greater thickness than sheets gradually increases.

Although gear drums are made of mild steel sheets with high formability, it is desirable to produce the gear drums from high-strength steel sheets. This is due in owing to the reduction in the weight of automobiles. However, the spline forming of high-strength steel cups having low formability is difficult due to severe deformation, in particular ultra-high strength steel cups.

To improve the formability in the spline forming of ultra-high strength steel gear drums, the side wall of a cup formed into a gear shape is heated by the resistance heating (**Image 4.2-10**).

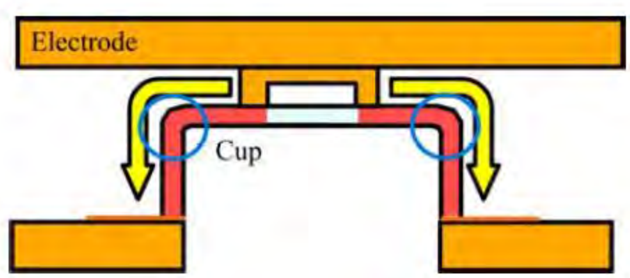



**Image 4.2-10: Resistance Heating of Side Wall in Hot Spline Forming of Gear Drum**
*(Source: Science Direct [http://www.ysxbcn.com/down/upfile/soft/20120106/43-p496.swf](http://www.ysxbcn.com/down/upfile/soft/20120106/43-p496.swf))*

The corner and edge of the side wall are in contact with the upper and lower electrodes, respectively. When the thickness of the side wall is kept uniform by applying ironing in the deep drawing of the cup, the side wall is uniformly heated by the electrification, namely, the cross-sectional area of the side wall is uniform in the current direction. In addition, no heating of the bottom of the cup has the function of preventing the rapture in the bottom during the spline forming. The applicable range of the resistance heating is extended to the spline forming.

The hot spline forming of a die-quenched gear drum using the resistance heating is shown in **Image 4.2-11**. The side wall of the resistance-heated drawn cup is ironed and then die-quenched. Since the resistance heating is very rapid, the cup is hardly oxidized.

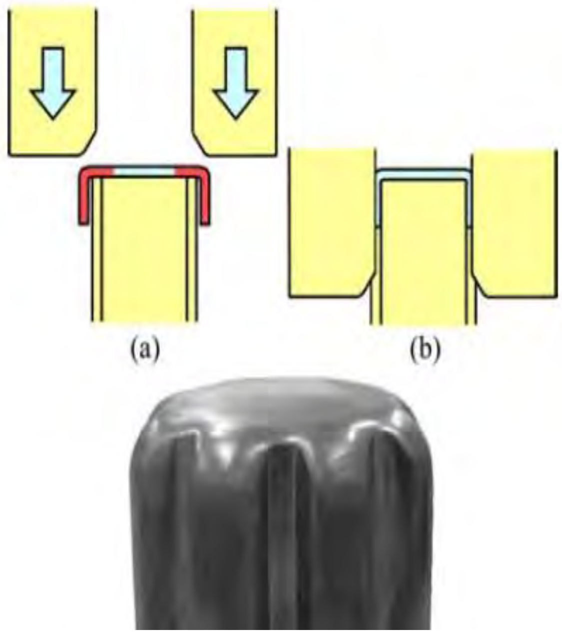



**Image 4.2-11: Hot Spline Forming of Die-quenched Gear Drum Using Resistance Heating**
**a) Heating at 900 °C; b) Die quenching; c) Formed Drum**
*(Source: Science Direct http://www.ysxbcn.com/down/upfile/soft/20120106/43-p496.swf)*

By using this process and high-strength steels to manufacture the various drive hubs in this system, a 10% mass weight savings is achieved.

**Table 4.2-16: Subsystem Mass Reduction and Cost Impact Estimates for Internal Clutch**

| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction Idea | | | | | |
| 02 | 04 | 00 | Internal Clutch Subsystem | | | | | | |
| 02 | 04 | 01 | Sprague / One-Way Clutches | | 0.336 | -$4.79 | -$14.28 | 15.00% | 0.01% |
| 02 | 04 | 02 | Brake & Clutch Asm | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 04 | 03 | Clutch & Brake Hubs | | 3.840 | -$34.21 | -$8.91 | 18.54% | 0.16% |
| 02 | 04 | 04 | Shafts, Sleeves & Couplers | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 04 | 05 | Clutch & Brake Discs & Plates | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 04 | 99 | Misc. | | 0.057 | -$0.94 | -$16.57 | 9.66% | 0.00% |
| | | | | X | 4.232 (Decrease) | -$39.94 (Increase) | -9.437 (Increase) | 13.89% | 0.17% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.2.5 Launch Clutch Subsystem

### 4.2.5.1 Subsystem Content Overview

As seen in **Table 4.2-17**, the most significant contributor to the Launch Clutch Subsystem mass is the torque converter. The torque converter transforms hydraulic pressure within the transmission to mechanical torque, which drives the drive shafts and, ultimately, the wheels. The Torque Converter Assembly Subsystem (**Image 4.2-12**) is a welded construction with SAE 1018 steel as its raw material.

**Image 4.2-12: Torque Converter**
*(Source: FEV, Inc.)*

**Table 4.2-17: Mass Breakdown by Sub-subsystem for Launch Clutch Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 05 | 00 | Launch Clutch Subsystem | |
| 02 | 05 | 01 | Torque Converter Asm | 19.320 |
| 02 | 05 | 99 | Misc. | 0.970 |
| | | | | |
| | | | Total Subsystem Mass = | 20.290 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 13.97% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.83% |

#### 4.2.5.2 Chevrolet Silverado Baseline Subsystem Technology

The Silverado's Launch Clutch Subsystem is a direct result of the traditional style transmission that was selected for it. The torque converter normally takes the place of a mechanical clutch in a vehicle with an automatic transmission, allowing the load to be separated from the power source. The present torque converter is an auto industry standard that has been used since the 1950s. Improvements on this unit will lead to a lighter and better drive system. The key characteristic of a torque converter is its ability to multiply torque when there is a substantial difference between input and output rotational speed, thus providing the equivalent of a reduction gear. Some of these devices are also equipped with a temporary locking mechanism that rigidly binds the engine to the transmission when their speeds are nearly equal, to avoid slippage and a resulting loss of efficiency. The Silverado torque converter has this lockup.

#### 4.2.5.3 Mass Reduction Industry Trends

Although DCT (Dual Clutch 7-8-9 speed Transmissions) have increased in popularity for fuel economy and mass weight savings, they are still more expensive than torque converter-style transmissions (depending, of course, on the vehicle segment). Although very efficient in most applications, the Silverado's duty cycle requirements exclude this type of transmission for consideration. Pulling a boat out of the water uses all the available horse power and torque that is available. This type of operational use demands an automatic transmission coupled to a torque converter or a manual clutch with a standard transmission. This configuration of transferring power from the engine to the drive line appears that it will be used for some time.

#### 4.2.5.4 Summary of Mass Reduction Concepts Considered

**Table 4.2-18** shows the mass reduction ideas considered for the Launch Clutch Subsystem. The Silverado gear train design is robust with exceptional consideration given to a heavy-duty life cycle. The torque converter was designed with the same operational intent. Replacing the industry standard steel torque converter with a plastic or aluminum unit would be a huge mass reduction improvement. Eliminating the torque converter completely by using a DCT-style transmission would be another option.

**Table 4.2-18: Summary of Mass Reduction Concepts Considered for the Launch Clutch System**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Torque Converter | Replace with plastic unit using DuPont Zytel HTN51LG50HSLBK083 | 75% weight save | Application still in R&D |
| Torque Converter | Replace steel with aluminum | 50% weight save | Medium risk moderate cost increase |
| Torque Converter | Replace with DCT transmission | 10% weight save | Application risk high |

#### 4.2.5.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected for this subassembly are shown in **Table 4.2-19**. Regarding the torque converter application, a full aluminum torque converter assembly was proposed, knowing that it will affect multiple platforms. Aluminum torque converters are being used in off-road, racing, and heavy industrial equipment and some automotive applications. A cast design of an aluminum turbine, impeller, and housing will reduce the assembly steps in process and make for a simpler assembly.

Since the current automatic transmission used in the Silverado requires a lockup of torque convertor to engine, aluminum torque convertor housing has not been an option. Metal Matrix Composite (MMC) technology enables the use of aluminum because it creates a wear-resistant surface for the lockup plate to engage. This surface will not gall, smear, or otherwise degrade causing a loss of coefficient of friction required for this system to operate correctly. Using an aluminum surface versus aluminum MMC would not allow the lock up to perform over the heavy-duty cycle that is required for the Silverado.

Companies currently operate that have the ability to reduce the overall mass of this unit. For example, Century, Inc. in Traverse City, Michigan, advertises proprietary technology and patented processes that allow for up to a 45% weight reduction in some vehicle components with the uses of MMCs to create strong, stiff, wear-resistant, vibration damped, and lightweight components. Century has developed a proprietary process to mass-produce MMC materials needed for the integrity of the torque converter. Century has done preliminary CAE calculations on key components of the unit to validate its proposal is sound. Further study is required to move to prototype, however.

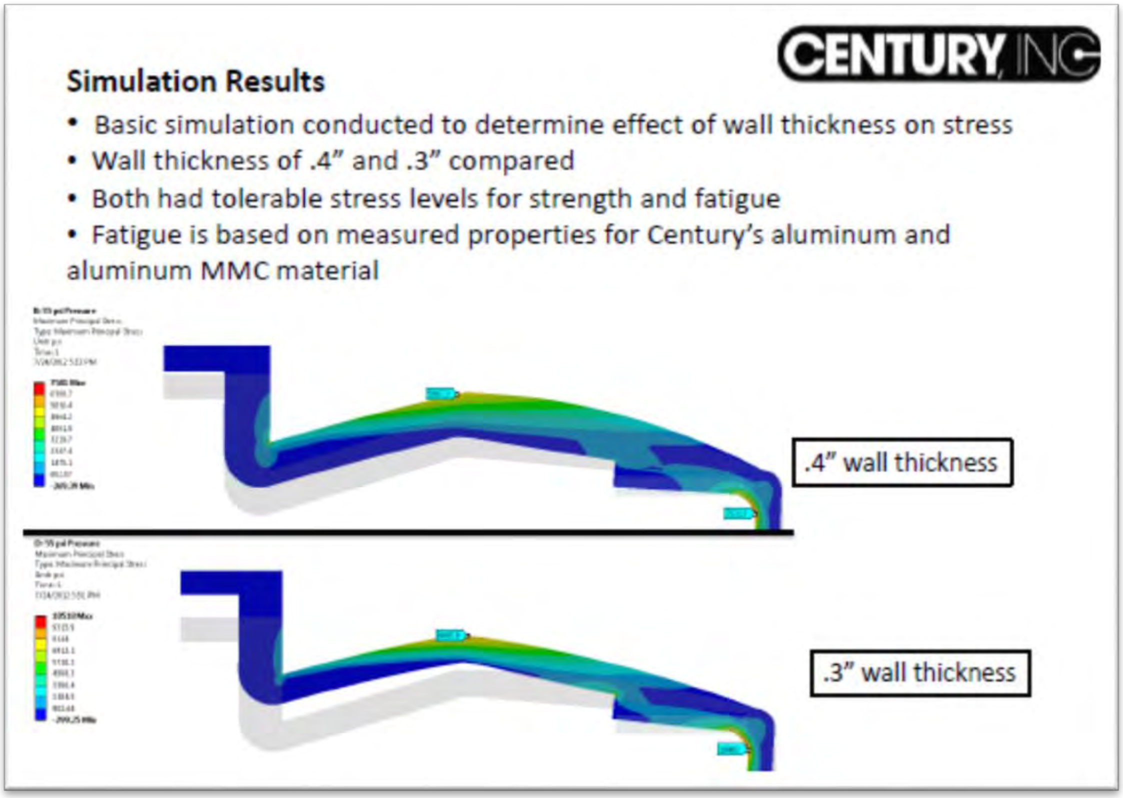



**Image 4.2-13: Torque Converter Front Cover**
*(Source: Century, Inc.)*

Alcast Aluminum Foundry in Peoria, Illinois, specializes in high-quality and high-precision American-made aluminum castings. It has designed a low-pressure, bottom-fill, electromagnetic, permanent mold-casting process specifically to provide top quality aluminum torque converter castings for its customers. Using a shell core process, Alcast can provide exceptionally smooth surface finishes. Along with segmented, helically drawn, or single-piece cores they can produce very exotic blade configurations in torque converters. Alcast has honed the processes of producing the required quality components needed for the OEMs that produce aluminum converter components.

The use of MMC preforms (**Image 4.2-14**) casted into the aluminum case sections will give the torque converter the integrity and light-weight physical characteristics required for this unit.

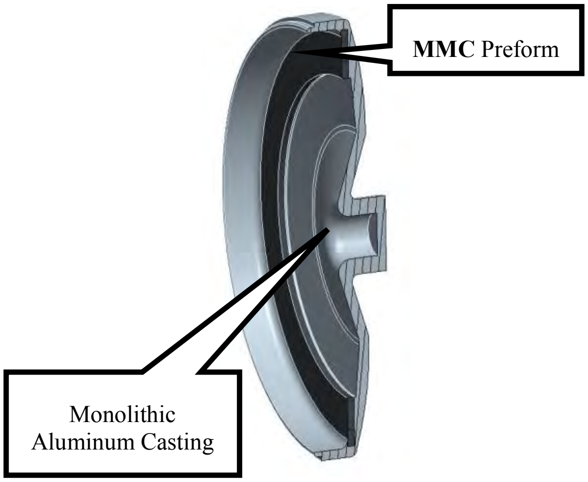



**Image 4.2-14: MMC Preform**
*(Source: FEV, Inc.)*

**Table 4.2-19: Mass Reduction Ideas Selected for Launch Clutch System**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 02 | 05 | 00 | **Launch Clutch Subsystem** | |
| 02 | 05 | 01 | Torque Converter | Replace steel torque converter with aluminum |

#### 4.2.5.6 Preliminary Mass Reduction and Cost Impact Estimates

The mass reductions in this subsystem were gained by the material selection as shown in **Table 4.2-20**. Using cast A356 aluminum, compared to the brazed steel unit (**Image 4.2-15**), will yield a 40% to 50% weight loss. This application is in the field today with the required material and technology in place to produce a good replacement for the traditional steel brazed converter.


**Image 4.2-15: Aluminum Torque Converter**
*(Sources: alcastcompany.com; FEV, Inc.)*

**Table 4.2-20: Subsystem Mass Reduction and Cost Impact Estimates for Launch Clutch System**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 02 | 05 | 00 | Launch Clutch Subsystem | | | | | | |
| 02 | 05 | 01 | Torque Converter Asm | | 8.622 | -$21.73 | -$2.52 | 44.63% | 0.35% |
| 02 | 05 | 99 | Misc. | | 0.000 | $0.00 | -- | -- | 0.00% |
| | | | | 1D | 8.622 (Decrease) | -$21.73 (Increase) | -2.521 (Increase) | 42.49% | 0.35% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.2.6 Oil Pump and Filter Subsystem

### 4.2.6.1 Subsystem Content Overview

As shown in **Table 4.2-21**, the most significant contributor to the Oil Pump and Filter Subsystem mass is the oil pump unit. The pump unit is cast iron in the Silverado teardown cost study.

**Table 4.2-21: Mass Breakdown by Sub-subsystem for Oil Pump and Filter Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 06 | 00 | Oil Pump and Filter Subsystem | |
| 02 | 06 | 01 | Oil Pump Asm | 4.707 |
| 02 | 06 | 02 | Covers | 0.000 |
| 02 | 06 | 03 | Filters | 0.439 |
| 02 | 06 | 04 | Oil Cooler | 2.350 |
| 02 | 06 | 05 | Oil Squirter | 0.000 |
| 02 | 06 | 10 | Plugs | 0.000 |
| 02 | 06 | 99 | Misc. | 0.000 |
| | | | | |
| | | | Total Subsystem Mass = | 7.496 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 5.16% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.31% |

#### 4.2.6.2 Chevrolet Silverado Baseline Subsystem Technology

The oil pump is a vane pump with cast aluminum housing. It has a powder metal pump slide and rotor that services to oil volume and pressure requirements of this transmission. A vane pump is used to ensure that there is adequate oil flow through the system to cool the transmission during extreme load conditions. This vehicle has a dedicated oil cooler as insurance against overheating, which could possibly damage the system.

#### 4.2.6.3 Mass Reduction Industry Trends

Every day, the auto manufacturing industry discovers or integrates new and innovative technologies that come to it from other sectors. In the case of the transmission oil pump, the racing industry has led the way in developing lightweight and efficient pumps. Aluminum, aluminum-magnesium alloys, and even plastic polymers are presently available. This is a great application by which to achieve mass weight reduction at a reasonable cost.

#### 4.2.6.4 Summary of Mass Reduction Concepts Considered

**Table 4.2-22** contains the mass reduction ideas considered for the Oil Pump and Filter Subsystem. Aluminum, magnesium, and plastic are viable materials for use in this application currently.

**Table 4.2-22: Summary of Mass Reduction Concepts Considered for the Oil Pump and Filter Subsystem**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Oil Pump Housing | Replace Aluminum with Magnesium | 10 to 30% weight save | No risk moderate cost increase |
| Oil Pump Housing | Replace Aluminum with Plastic | 30 to 50% weight save | Engineered solution dependent some risk |
| Oil Cooler Brackets | Replace steel with Aluminum | 30 to 40% weight save | Low risk cost save |

#### 4.2.6.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected from this subassembly are shown in **Table 4.2-23**. There are pump suppliers, such as Scherzinger Pump Technology, that produce state-of-the-art magnesium and aluminum pumps for the racing world today (**Image 4.2-16**). These companies are supplying lightweight transmission solutions and can help bring innovative pump approaches to the automotive industry.

**Table 4.2-23: Mass Reduction Ideas Selected for Oil Pump and Filter Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 02 | 06 | 00 | **Oil Pump & Filter Subsystem** | |
| 02 | 06 | 01 | Oil Pump Asm | Replace aluminum with magnesium |
| 02 | 06 | 04 | Oil Cooler | Steel bracket to aluminum |
| 02 | 06 | 99 | Misc. | n/a |


**Image 4.2-16: Aluminum Oil Pump Assembly**
*(Source: Samarins.com)*

#### 4.2.6.6 Preliminary Mass Reduction and Cost Impact Estimates

The subsystem's mass reductions were gained through the material selection shown in **Table 4.2-24**. The use of a magnesium MRI 153M instead of the aluminum AA390 alloy reduced the weight of the assembly by 40%. Similar applications are used by racing component manufacturers and some OEMs to lighten transmissions.

**Table 4.2-24: Preliminary Subsystem Mass Reduction and Cost Impact Estimates for the Oil Pump and Filter System**

| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction Idea | | | | | |
| 02 | 06 | 00 | Oil Pump and Filter Subsystem | | | | | | |
| 02 | 06 | 01 | Oil Pump Asm | | 1.442 | -$12.27 | -$8.51 | 30.65% | 0.06% |
| 02 | 06 | 02 | Covers | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 06 | 03 | Filters | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 06 | 04 | Oil Cooler | | 0.977 | $0.75 | $0.77 | 41.56% | 0.04% |
| 02 | 06 | 05 | Oil Squirter | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 06 | 10 | Plugs | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 06 | 99 | Misc. | | 0.000 | $0.00 | -- | -- | 0.00% |
| | | | | 1D | 2.419 (Decrease) | -$11.52 (Increase) | -4.762 (Increase) | 32.27% | 0.10% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.2.7 Mechanical Controls Subsystem

### 4.2.7.1 Subsystem Content Overview

As shown in **Table 4.2-25**, the most significant contributor to the mass of the Mechanical Controls Subsystem is the valve body unit. The Silverado's valve unit is cast aluminum.

**Table 4.2-25: Mass Breakdown by Sub-subsystem for Mechanical Controls Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 07 | 00 | Mechanical Controls Subsystem | |
| 02 | 07 | 01 | Valve Body Asm | 6.557 |
| 02 | 07 | 02 | Gear Selector System | 0.581 |
| | | | | |
| | | | Total Subsystem Mass = | 7.138 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 4.91% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.29% |

#### 4.2.7.2 Chevrolet Silverado Baseline Subsystem Technology

The control valve is a two-piece construction, aluminum diecast valve body that handles the shifting requirements of this transmission from gear to gear. This style of control valve has been used in this configuration for more than a decade.

#### 4.2.7.3 Mass Reduction Industry Trends

With the increased number of gear change options being introduced by automatic transmission designers, a need for a more sophisticated control mechanism has been identified. The expectation is a lighter, more efficient, and cost neutral product for the customer. The choices are plastic, magnesium, or MMC of some sort will improve the performance of the control valve.

#### 4.2.7.4 Summary of Mass Reduction Concepts Considered

**Table 4.2-26** shows the mass reduction ideas considered for the Mechanical Controls Subsystem. Magnesium, plastic, and MMC are viable materials presently used in this application.

**Table 4.2-26: Summary of Mass Reduction Concepts Considered for the Mechanical Control Subsystem**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Control Valve | Replace Aluminum with Magnesium | 20 to 30% weight save | Low risk low cost |
| Control Valve | Replace Aluminum with Plastic | 50% weight save | Still in R&D cost neutral |
| Control Valve | Replace Aluminum wit MMC | 20 to 30% weight save | Low risk high cost |

### 4.2.7.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected from this subassembly are shown in **Table 4.2-27**. The control valve body is a diecast component that has the opportunity to be lightened. There are drivetrain product suppliers such as Metaldyne that are currently producing state-of-the-art aluminum diecast (**Image 4.2-17**) valve bodies for OEMs worldwide. These companies are supplying lightweight transmission solutions and can help introduce new, innovative control valve approaches to the automotive industry.

**Table 4.2-27: Mass Reduction Ideas Selected for Mechanical Control Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 02 | 07 | 00 | **Mechanical Controls Subsystem** | |
| 02 | 07 | 01 | Valve Body Asm | Replace aluminum with magnesium |
| 02 | 07 | 02 | Gear Selector System | n/a |
| 02 | 07 | 99 | Misc | n/a |

**Image 4.2-17: Aluminum Valve Body Assembly**
*(Source: FEV, Inc.)*

### 4.2.7.6 Mass reduction and Cost Impact Estimates

The mass reductions in this subsystem were gained by the material selection as shown in **Table 4.2-28**. The use of a magnesium MRI 153M instead of the aluminum AA390 alloy will reduce the weight of the assembly by 40%. Similar applications are currently being used by racing component manufacturers and some OEMs to lighten their transmissions.

**Table 4.2-28: Subsystem Mass Reduction and Cost Impact Estimates for Mechanical Controls Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 02 | 07 | 00 | Mechanical Controls Subsystem | | | | | | |
| 02 | 07 | 01 | Valve Body Asm | | 0.872 | -$5.03 | -$5.76 | 13.30% | 0.04% |
| 02 | 07 | 02 | Gear Selector System | | 0.000 | $0.00 | -- | -- | 0.00% |
| | | | | X | 0.872 (Decrease) | -$5.03 (Increase) | -5.763 (Increase) | 12.22% | 0.04% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.2.8 Electrical Controls Subsystem

After a systematic investigation, it is determined there are no opportunities for mass reduction or cost benefits in this subsystem (**Table 4.2-29**).

**Table 4.2-29: Mass Breakdown by Sub-subsystem for Electrical Controls**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 08 | 00 | Electrical Controls Subsystem | |
| 02 | 08 | 01 | Controller | 1.600 |
| 02 | 08 | 02 | Connector / Electrical Integrator Asm | 2.533 |
| 02 | 08 | 03 | Sensors | 0.000 |
| 02 | 08 | 04 | Switch | 0.166 |
| 02 | 08 | 99 | Misc. | 0.000 |
| | | | | |
| | | | Total Subsystem Mass = | 4.299 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 2.96% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.18% |

### 4.2.9 Parking Mechanism Subsystem

#### 4.2.9.1 Subsystem Content Overview

As **Table 4.2-30** shows, the Silverado Parking Mechanism Subsystem consists of shift linkage externally connected to the steering column and parking mechanism internal to the transmission. This system configuration has been with the Silverado for a decade (**Image 4.2-18**).

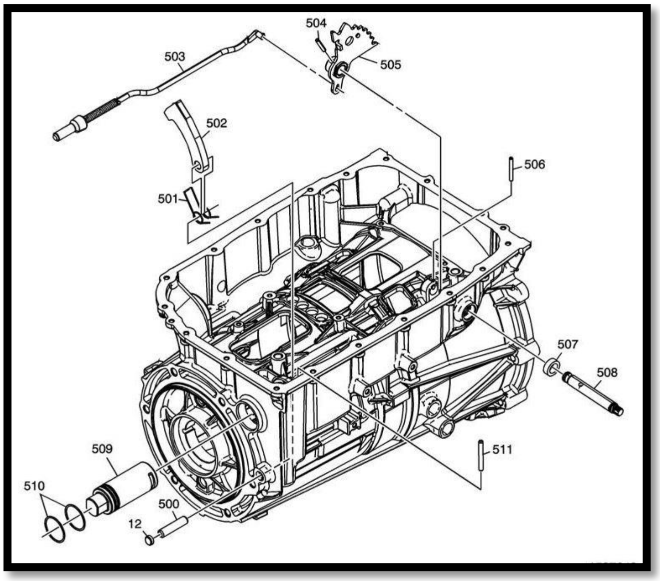



**Image 4.2-18: Parking Mechanism Subsystem**
*(Source: Nalley Auto)*

**Table 4.2-30: Mass Breakdown by Sub-subsystem for Parking Mechanism Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 09 | 00 | Parking Mechanism Subsystem | |
| 02 | 09 | 01 | Shafts / Rods | 0.000 |
| 02 | 09 | 03 | Pawls | 0.876 |
| | | | | |
| | | | Total Subsystem Mass = | 0.876 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 0.60% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.04% |

### 4.2.9.2 Chevrolet Silverado Baseline Subsystem Technology

The most significant contributor to the mass of the Parking Mechanism Subsystem is the parking pawl unit, which is made of steel stamping.

#### 4.2.9.3 Mass Reduction Industry Trends

Examining this system, a complete mechanical way to lock up the transmission without compromising safety is a benefit; safety and convenience drive a robust locking system. The current trend in the industry is to lighten this mechanism while ensuring its safety and effectiveness.

#### 4.2.9.4 Summary of Mass Reduction Concepts Considered

**Table 4.2-31** contains the mass reduction ideas considered for the Parking Mechanism Subsystem. Our expectations would be a high-strength steel, MMC, and MMCL of some sort to improve the system.

**Table 4.2-31: Summary of Mass Reduction Concepts Considered for the Parking Mechanism Subsystem**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Linkage | Replace 1018 CRS with high strength steel | 5 to 10% weight save | Low risk low cost |
| Linkage | Replace 1018 CRS with Aluminum | 50% weight save | High risk high cost |
| Linkage | Replace 1018 CRS with CCF | 60% weight save | Low risk high cost |
| Pawl | Replace 1020 CRS with high strength steel | 5 to 10% weight save | Low risk low cost |
| Pawl | Replace 1020 CRS with MMCL | 50% weight save | Still in R&D cost neutral |
| Pawl | Replace 1020 CRSI with MMC | 20 to 30% weight save | Low risk high cost |

#### 4.2.9.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected from this subassembly are shown in **Table 4.2-32.** The Parking Mechanism Subsystem is composed of cold roll steel components that have little opportunity for lightening. There are materials selections, however, that would help shed some mass without compromising the safety aspect of some components: Ti-SB62 is made via the conventional wrought processing route. Then, during an in-situ process, titanium-boride (TiB) is formed. The TiB phase is responsible for the unique properties of this titanium-boron alloy. Because of this process, no voids or defects are found like in powder based titanium alloys. This material would make a great replacement for the parking pawl: its 4.55 density will help system mass reduction (**Image 4.2-19**). There are also MMCs in the marketplace today that will find themselves in future transmissions. We have looked at them for help to reduce weight in other components.

**Table 4.2-32: Subsystem Mass Reduction and Cost Impact Estimates for Parking Mechanism Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 02 | 09 | 00 | **Parking Mechanism Subsystem** | |
| 02 | 09 | 01 | Shafts / Rods | n/a |
| 02 | 09 | 03 | Pawls | Replace 1020 CRS with TI-SB62 |
| 02 | 09 | 99 | Misc. | n/a |

**Image 4.2-19: Steel Parking Pawl**
*(Source: FEV, Inc.)*

#### 4.2.9.6 Mass Reduction and Cost Impact Estimates

The mass reductions in this subsystem were gained by the material selection as shown in **Table 4.2-33**. The use of TI-SB62 for the Parking Pawl will reduce the weight of the component by approximately 40%, similar application are used by aerospace component manufacturers to lighten their transmissions and some OEMs with the same intent.

**Table 4.2-33: Subsystem Mass Reduction and Cost Impact Estimates for Parking Mechanism Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 02 | 09 | 00 | Parking Mechanism Subsystem | | | | | | |
| 02 | 09 | 01 | Shafts / Rods | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 09 | 03 | Pawls | | 0.060 | $5.24 | $87.45 | 6.84% | 0.00% |
| | | | | 1A | 0.060 (Decrease) | $5.24 (Decrease) | 87.455 (Decrease) | 6.84% | 0.00% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.2.10 Miscellaneous Subsystem

After a systematic investigation it was determined there are no opportunities for mass reduction or cost benefits in this subsystem (**Table 4.2-34**).

**Table 4.2-34: Mass Breakdown by Sub-subsystem for Miscellaneous Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 02 | 10 | 00 | Misc. Subsystem | |
| 02 | 10 | 01 | Plugs | 0.000 |
| 02 | 10 | 99 | Misc. | 0.000 |
| | | | Total Subsystem Mass = | 0.000 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 0.00% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.00% |

## 4.2.11 Electric Motor and Controls Subsystem

After a systematic investigation it was determined there are no opportunities for mass reduction or cost benefits in this subsystem (**Table 4.2-35**).

**Table 4.2-35: Mass Breakdown by Sub-subsystem for Electric Motor and Controls**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 11 | 00 | Electric Motor & Controls Subsystem | |
| 02 | 11 | 99 | Misc. | 0.000 |
| | | | | |
| | | | Total Subsystem Mass = | 0.000 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 0.00% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.00% |

### 4.2.12 Transfer Case Subsystem

#### 4.2.12.1 Subsystem Content Overview

As seen in **Table 4.2-36**, the Transfer Case Subsystem is a complex two-speed multi-drive gear box (NP263) built by Magna for GM (**Image 4.2-20**). This unit is currently used in many GM platforms and meets the needs of the many vehicles on which it is utilized.

The Magna Powertrain (MP) model 3023/3024 RPO NQH transfer case is a two-speed automatic, active transfer case (ATC). The MP 3023/3024 ATC provides five modes: Auto 4WD, 4HI, 4LO, 2HI, and Neutral. Transfer cases are classified as either "divorced/independent" or "married." Married cases are those bolted directly to the transmission, as is done in the Silverado. There are two different types of internal workings found in most transfer cases: gear-driven and chain-driven. The Silverado has chain-drive, which has proven to be a quieter unit for the platform duty requirements. The Silverado teardown T-case has aluminum housing and all-steel inner components.

**Image 4.2-20: 6L80e Transmission and Transfer Case**
*(Source: ATSG)*

**Table 4.2-36: Mass Breakdown by Sub-subsystem for Driver Operated External Controls Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 12 | 00 | Transfer Case Subsystem | |
| 02 | 12 | 01 | Carrier | 1.951 |
| 02 | 12 | 02 | Planetary Gears | 3.661 |
| 02 | 12 | 03 | Drive Gears & Shafts | 12.753 |
| 02 | 12 | 04 | Clutch & Brake Hubs | 3.721 |
| 02 | 12 | 05 | Shift Fork Assembly | 1.745 |
| 02 | 12 | 06 | Drive Chain | 2.262 |
| 02 | 12 | 07 | Bearings & Spacers | 1.186 |
| 02 | 12 | 08 | Case Pump | 0.630 |
| 02 | 12 | 10 | Actuator Electiric Motors & Sensors | 0.000 |
| 02 | 12 | 99 | Misc. | 0.530 |
| | | | | |
| | | | Total Subsystem Mass = | 28.439 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 19.58% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.16% |

#### 4.2.12.2 Silverado Baseline Subsystem Technology

The Silverado transfer case receives power from the transmission then sends it to both the front and rear axles. The driver can put the transfer case into either two- or four-wheel-drive mode. This is sometimes accomplished by means of a shifter, similar to that in a manual transmission. The Auto 4WD position allows the capability of an active transfer case, which provides the benefits of on-demand torque biasing wet clutch and easy vehicle tuning through software calibrations. The software calibrations allow more features such as flexible adapt ready position and clutch preload torque levels. The technology allows for vehicle speed-dependent clutch torque levels to enhance the performance of the system. The system is calibrated to provide 0-6.78 N·m (0-5 lb. ft.) of clutch torque during low-speed, low-engine torque operation, and predetermined higher torque for 40 km/h (25 mph) and greater. This prevents crow-hop and binding at low speeds and provides higher torque biases at higher vehicle speeds in order to enhance stability.

#### 4.2.12.3 Mass Reduction Industry Trends

There are vehicle manufacturers that have adopted some light-weighting options in their T-Case designs, such as BorgWarner and Magna, which have been upgrading their offering to OEMs on an annual basis. It is the OEMs, however, that drive the specification of the unit: Reliable, quiet, lightweight and lastly cost-effective are the directives to the supply base for these units. Expect to see a more compact and lighter unit on the next generation four wheel drive vehicles with high strength steels and MMCs helping to accomplish the task.

#### 4.2.12.4 Summary of Mass Reduction Concepts Considered

**Table 4.2-37** is the compilation of the mass reduction ideas considered for the Transfer Case Subsystem. Material selection and light-weighting techniques will affect our options to reduce mass.

**Table 4.2-37: Summary of Mass Reduction Concepts Initially Considered for the Transfer Case Subsystem**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Planetary Carrier | Replace PM M4 with C64 forging | 10 to 30% weight save | No risk, cost increase |
| Planetary Carrier | Replace PM M4 with Steel Stamping | 30 to 50% weight save | Engineered solution dependent some risk |
| Planetary Carrier | Replace PM M4 With MMC | 30 to 40% weight save | Low risk cost increase |
| Sun & Pinion Gears | Replace 1090 with 9310 | 30 to 40% weight save | Low risk menamul cost increase |
| Sun & Pinion Gears | Replace 1090 with C61 | 30 to 40% weight save | Low risk cost increase |
| Sun & Pinion Gears | Replace 1090 with Pyro 53 | 30 to 40% weight save | Low risk cost increase |
| Output Shafts | Replace 1040 bar stock with Mubea tube 9310 | 20 to 30% weight save | Low risk menamul cost increase |
| Output Shafts | Replace 1040 bar stock with Mubea tube C64 | 30 to 40% weight save | Low risk cost increase |
| Output Shafts | Replace 1040 bar stock with Mubea tube Pyro 53 | 20 to 30% weight save | Low risk cost increase |

### 4.2.12.5 Selection of Mass Reduction Ideas Selected

The mass reduction ideas selected from this subassembly are shown in **Table 4.2-38**. Components shown utilize materials that will meet the integrity needs of the system and fulfill the mass reduction parameters

**Table 4.2-38: Mass Reduction Ideas Selected for Transfer Case Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 02 | 12 | 00 | **Transfer Case Subsystem** | |
| 02 | 12 | 01 | Carrier | Replace PM with Stamped Steel |
| 02 | 12 | 02 | Planetary Gears | Replace 1090 with 9310 |
| 02 | 12 | 03 | Drive Gears & Shafts | Replace Bar stock with Mubea tube |
| 02 | 12 | 04 | Clutch & Brake Hubs | Replace PM M4 with MMC |
| 02 | 12 | 05 | Shift Fork Assembly | Replace PM steel with AL-MMC 2 |
| 02 | 12 | 06 | Drive Chain | n/a |
| 02 | 12 | 07 | Bearings & Spacers | Replace Steel Bearings with Vespel |
| 02 | 12 | 08 | Case Pump | Steel tube to Plastic |
| 02 | 12 | 10 | Actuator Electric Motor & Sensors | n/a |
| 02 | 12 | 99 | Misc. | n/a |

#### 4.2.12.6 Mass Reduction and Cost Impact Estimates

The mass reductions in this subsystem were gained by the material selection as shown in **Table 4.2-39**. With the use of aerospace materials the weight of the components in this subsystem are reduced by approximately 3.63% with a cost hit of only $0.11 per kg. These materials will be cost-effective by 2020, helping the industry to maintain integrity of their deliverable at a cost that will be affordable to the public.

**Table 4.2-39: Subsystem Mass Reduction and Cost Impact Estimates for Transfer Case Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 02 | 12 | 00 | Transfer Case Subsystem | | | | | | |
| 02 | 12 | 01 | Carrier | | 0.293 | $3.60 | $12.31 | 15.00% | 0.01% |
| 02 | 12 | 02 | Planetary Gears | | 0.488 | -$6.43 | -$13.17 | 13.33% | 0.02% |
| 02 | 12 | 03 | Drive Gears & Shafts | | 2.249 | -$33.00 | -$14.68 | 17.63% | 0.09% |
| 02 | 12 | 04 | Clutch & Brake Hubs | | 0.140 | -$20.38 | -$145.57 | 3.76% | 0.01% |
| 02 | 12 | 05 | Shift Fork Assembly | | 1.004 | $9.57 | $9.53 | 57.54% | 0.04% |
| 02 | 12 | 06 | Drive Chain | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 12 | 07 | Bearings & Spacers | | 0.883 | -$2.63 | -$2.98 | 74.49% | 0.04% |
| 02 | 12 | 08 | Case Pump | | 0.214 | $0.46 | $2.16 | 33.97% | 0.01% |
| 02 | 12 | 10 | Actuator Electiric Motors & Sensors | | 0.000 | $0.00 | -- | -- | 0.00% |
| 02 | 12 | 99 | Misc. | | 0.000 | $0.00 | -- | -- | 0.00% |
| | | | | X | 5.271 (Decrease) | -$48.81 (Increase) | -9.260 (Increase) | 0.00% | 0.21% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.2.13 Driver Operated External Controls Subsystem

After a systematic investigation, it was determined there are no opportunities for mass reduction or cost benefits in this subsystem (**Table 4.2-40**).

**Table 4.2-40: Mass Breakdown by Sub-subsystem for Driver Operated External Controls Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 02 | 20 | 00 | Driver Operated External Controls Subsystem | |
| 02 | 20 | 01 | Shift Module Assembly | 3.088 |
| 02 | 20 | 99 | Misc. | 0.042 |
| | | | | |
| | | | Total Subsystem Mass = | 3.130 |
| | | | Total System Mass = | 145.276 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 2.15% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.13% |

### 4.2.14 Secondary Mass Reduction / Compounding

The secondary mass reduction was obtained by an overall 20% mass reduction of the vehicle and this affected some of the transmission components by a 5.0 to 7.0% reduction.

#### 4.2.14.1 Component Reduction

The base Silverado transmission weighed 145.3 kg. The new weight after a full system review garnered a weight of 110.9 kg. A compounding reduction of approximately 7.0% of selected load and torque bearing components brought the overall weight down to 105.93 kg.

#### 4.2.14.2 Transmission size reduction

The overall dimensions of the transmission after downsizing performed during the analysis would only allow approximately 150 to 200 milometers reduction off the overall length of the system. Weight reduction was achievable but reducing the package size will be difficult.

**Table 4.2-41** shows the secondary mass reduction and what the total reduction would be.

**Table 4.2-41: Calculated Material Content Between the Base BOM and the Compounded BOM**

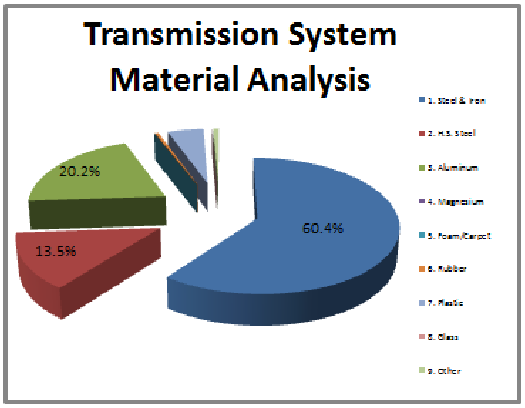
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction | | | | | | | |
| 02 | 00 | 00 | **Transmission System** | | | | | | | | |
| 02 | 01 | 00 | External Components | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 02 | 02 | 00 | Case Subsystem | 10.7 | 1.27 | 11.9 | -$30.60 | $5.09 | -$25.50 | -$2.14 | 0.49% |
| 02 | 03 | 00 | Gear Train Subsystem | 2.05 | 0.650 | 2.70 | $24.18 | $2.41 | $26.59 | $9.84 | 0.11% |
| 02 | 04 | 00 | Internal Clutch Subsystem | 4.23 | 1.18 | 5.41 | -$39.94 | $8.53 | -$31.41 | -$5.80 | 0.22% |
| 02 | 05 | 00 | Launch Clutch Subsystem | 8.62 | 1.13 | 9.7 | -$21.73 | $2.42 | -$19.32 | -$1.98 | 0.40% |
| 02 | 06 | 00 | Oil Pump and Filter Subsystem | 2.42 | 0.044 | 2.46 | -$11.52 | $1.79 | -$9.73 | -$3.95 | 0.10% |
| 02 | 07 | 00 | Mechanical Controls Subsystem | 0.872 | 0.146 | 1.02 | -$5.03 | $1.68 | -$3.35 | -$3.29 | 0.04% |
| 02 | 08 | 00 | Electrical Controls Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 02 | 09 | 00 | Parking Mechanism Subsystem | 0.060 | 0.00 | 0.064 | $5.24 | $0.31 | $5.55 | $86.61 | 0.00% |
| 02 | 10 | 00 | Misc. Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 02 | 11 | 00 | Electric Motor & Controls Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 02 | 12 | 00 | Transfer Case Subsystem | 5.27 | 0.743 | 6.01 | -$48.81 | $9.41 | -$39.40 | -$6.55 | 0.25% |
| 02 | 20 | 00 | Driver Operated External Controls Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| | | | | **34.2** (Decrease) | **5.17** (Decrease) | **39.4** (Decrease) | **-$128.20** (Increase) | **$31.64** (Decrease) | **-$96.57** (Increase) | **-$2.45** (Increase) | **1.60%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.2.15 Transmission System Material Analysis

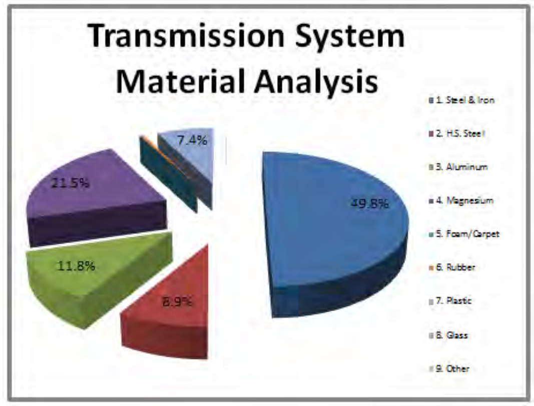
A material breakdown for the base Transmission System and for the light weighted and compounded Transmission System is provided in **Figure 4.2-2**. The "Steel & Iron" content category was reduced by more than 10%, while "Magnesium" and "Plastic" increased by 22% and 2.6%, respectively.

**Baseline Transmission System**




| | | Material Categories: |
|---|---|---|
| 60.4% | 87.748 | 1. Steel & Iron |
| 13.5% | 19.592 | 2. H.S. Steel |
| 20.2% | 29.301 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.5% | 0.681 | 6. Rubber |
| 4.8% | 6.945 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.7% | 1.010 | 9. Other |
| 100% | 145.276 | TOTAL |

**Total Mass Reduced Transmission System**




| | | Material Categories: |
|---|---|---|
| 49.8% | 51.722 | 1. Steel & Iron |
| 8.9% | 9.259 | 2. H.S. Steel |
| 11.8% | 12.213 | 3. Aluminum |
| 21.5% | 22.355 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.5% | 0.504 | 6. Rubber |
| 7.4% | 7.714 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.0% | 0.015 | 9. Other |
| 100% | 103.782 | TOTAL |

**Figure 4.2-2: Calculated Transmission System Baseline Material and Total Material Content**

## 4.3 Body System Group -B- (Interior)

Body System Group -B- includes the subsystems shown in **Table 4.3-1**. The largest mass contributors are the Seating, Interior Trim, and Instrument Panel/Console Subsystems. As seen in **Table 4.3-25**, a substantial amount of mass (34.02 kg) is reduced from Body System Group -B-. This provides a cost increase of $127.23 and an increase of $3.74 per kg. The largest contributor of this mass and cost reduction is the Seating Subsystem, followed by the Interior Trim and the Instrument Panel Subsystems.

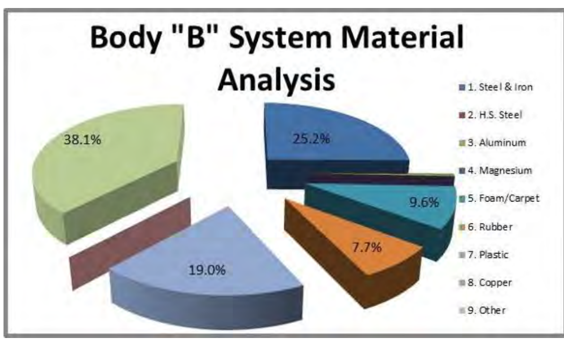
**Table 4.3-1: Baseline Subsystem Breakdown for Body System Group -B-**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 00 | 00 | **Body Group B** | |
| 03 | 05 | 00 | Interior Trim and Ornamentation Subsystem | 56.545 |
| 03 | 06 | 00 | Sound and Heat Control Subsystem (Body) | 4.784 |
| 03 | 07 | 00 | Sealing Subsystem | 14.516 |
| 03 | 10 | 00 | Seating Subsystem | 120.690 |
| 03 | 12 | 00 | Instrument Panel and Console Subsystem | 30.837 |
| 03 | 20 | 00 | Occupant Restraining Device Subsystem | 19.645 |
| | | | **Total System Mass =** | **247.017** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **System Mass Contribution Relative to Vehicle =** | **10.07%** |

**Table 4.3-2: Mass-Reduction and Cost Impact for Body System Group -B-**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys./ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | 2454 | | | | | | |
| 03 | 00 | 00 | Body Group B | | | | | | |
| 03 | 05 | 00 | Interior Trim and Ornamentation Subsystem | | 2.06 | $6.84 | $3.32 | 3.65% | 0.08% |
| 03 | 06 | 00 | Sound and Heat Control Subsystem (Body) | | 0.00 | $0.00 | -- | -- | 0.00% |
| 03 | 07 | 00 | Sealing Subsystem | | 4.72 | $32.23 | $6.84 | 32.48% | 0.19% |
| 03 | 10 | 00 | Seating Subsystem | | 19.2 | -$127.89 | -$6.68 | 15.87% | 0.78% |
| 03 | 12 | 00 | Instrument Panel and Console Subsystem | | 6.82 | -$35.29 | -$5.17 | 22.13% | 0.28% |
| 03 | 20 | 00 | Occupant Restraining Device Subsystem | | 1.26 | -$3.12 | -$2.47 | 6.42% | 0.05% |
| | | | | X | 34.0 (Decrease) | -$127.23 (Increase) | -$3.74 (Increase) | 13.77% | 1.39% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase




| | | Material Categories: |
|---|---|---|
| 25.2% | 62.227 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.4% | 1.111 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 9.6% | 23.694 | 5. Foam/Carpet |
| 7.7% | 18.898 | 6. Rubber |
| 19.0% | 47.010 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 38.1% | 94.077 | 9. Other |
| 100% | 247.017 | TOTAL |

**Figure 4.3-1: Calculated Material Content for the Body System -B- Base BOM**

### 4.3.1 Interior Trim and Ornamentation Subsystem

#### 4.3.1.1 Subsystem Content Overview

The Chevrolet Silverado uses a conventional interior trim package as well as upgrade packages. Considerable focus has been paid to the interior regarding the different types of materials used: plastic, rubber, cloth, leather, and steel. As with many of today's vehicle manufacturers, the larger amount of the vehicle sought for weight reductions are those areas which can do so without sacrificing looks, comfort, or performance.

**Table 4.3-3: Sub-subsystem Breakdown for Interior Trim and Ornamentation Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 03 | 05 | 00 | Interior Trim and Ornamentation Subsystem | |
| 03 | 05 | 01 | Main Floor Trim | 9.309 |
| 03 | 05 | 02 | NVH Pads | 12.911 |
| 03 | 05 | 03 | Headliner Assembly | 5.278 |
| 03 | 05 | 04 | Sun Visors | 1.261 |
| 03 | 05 | 05 | Front RH & LH Door Trim Panel | 9.864 |
| 03 | 05 | 06 | Rear Door or Rear Quarter Trim Panel | 5.676 |
| 03 | 05 | 07 | Pillar Trim Lower | 5.583 |
| 03 | 05 | 08 | Pillar Trim Upper | 2.825 |
| 03 | 05 | 09 | Floor Mats - OEM | 3.838 |
| | | | | |
| | | | Total Subsystem Mass = | 56.545 |
| | | | Total System Mass = | 247.017 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 22.89% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 2.30% |

**Image 4.3-1: Chevrolet Silverado Interior**
*(Source: FEV, Inc.)*

#### 4.3.1.2 Mass Reduction Industry Trends

Industry trends for mass reduction in the interior include many different considerations due to the fact that the interior trim is made up of many different components and materials. Among the ways to reduce mass includes reducing the density of the vinyl trim or the thickness of the vinyl trim. Mass density can be reduced by using PolyOne® foaming additives during the injection molding process. Using carbon fiber as a replacement for vinyl trim results in mass reduction, although doing so will add cost to the interior due to carbon fiber's limited availability and raw material cost. Products and techniques using light-weight wood, wood fiber, or foam with a laminated interior surface treatment also involve added processing.

PolyOne is a microcellular foam injection molding process for thermoplastics materials that injects a foaming agent into the plastic during the injection stage of the molding process. PolyOne is used in many applications, automotive, medical and the packaging industry. The process is currently used by major OEM's. The quality advantages of the PolyOne Process are complemented by certain direct economic advantages, including the ability to produce 20-33% more parts per hour on a given molded machine then current production methods, and the ability to mold parts on lower tonnage machines as a result of the viscosity reduction.

PolyOne has a foaming agent incorporated into pellets which can be added directly into a standard mold machine plastic hopper and mixed with base material plastic pellets to provide the proper ratio of foaming agent to the base material. PolyOne can be used on Class "A" surfaces. All parts were quoted with a 10% mass reduction.

PolyOne Corporation is a global supplier of polymer materials, services, and solutions. They also specialize in performance materials, colors and additives, thermoplastic elastomers, coatings and resins, and inks, among other things. The industries they serve include building and construction, electrical and electronics, healthcare, industrial, packaging, and transportation.

Of particular interest to this study is PolyOne's OnCap™ Chemical Foaming Agents (CFAs), which is a part of its OnCap Additives product line. This line is part of PolyOne's Global Color, Additives and Inks business unit. In typical industry use, these CFAs provide a multitude of benefits to improve polymer processing in a variety of situations. They can also reduce the weight of the plastic part to which they are added. CFAs are formulated products that will decompose in a polymer during processing at a specific temperature and liberate a gas that will form a controlled cellular structure in the solid phase of the polymer.[39]

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39 *PolyOne® presentation information provided by PolyOne*

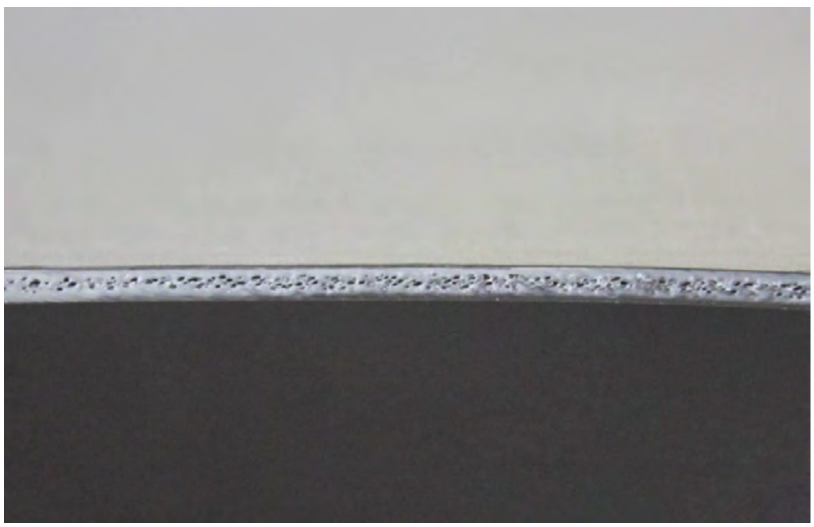



**Image 4.3-2: Sample Part Cross Section View**
*(Source: PolyOne presentation information)*


**Image 4.3-3: Sample Part Front Face View of Class "A" Surface with PolyOne**
*(Source: FEV, Inc. photograph of part supplied by PolyOne)*

PolyOne's OnCap CFA additive family of density reduction and anti-sink technologies provide customized solutions enabling you to reduce scrap rates caused by sink marks and become cost effective by off-setting resin costs. OnCap CFA technology has been tested and proven and is compatible across a wide range of polymers.

OnCap CFA will positively impact cost in the following ways:

**Reduce Part Weight Without compromising performance[40]:**
The most direct way that reducing your part density will improve your profitability, is by displacing resin costs.

**Improved Production Efficiencies:**

- Density reductions typically range from 10-50%.
- Operational savings through less scrap
- Redesign for better utilization of the OnCap™ product.
- Reduced Scrap– more profits derived from increased part quality.
- Density Reduction– Resin Cost off-set, competitive advantage for new and existing business.

Examples: automotive parts such as dash frames, and fan guards can achieve a considerable weight reduction.

40 *(Source: http://www.polyone.com/en-us/docs/Documents/OnCap%20Chemical%20Foaming%20Agents.pdf)*

**Image 4.3-4: Sample part front face view**
*(PolyOne® presentation information provided by PolyOne)*

**Image 4.3-5: Silverado IP Main Molding**
*(Source: FEV, Inc.)*

**Why OnCap Foaming Agents?** OnCap Foaming Agents grow the bottom line by:

- **Reducing Material Usage**
  Customers have achieved up to 50% reductions in material usage while maintaining finished part integrity.
- **Finished Part Weight Reduction**
  Reduced weight of finished products can improve fuel efficiency and reduce shipping costs.
- **Improving Quality**
  Sink mark surface defects are minimized due to consistent mold cavity pressure provided by OnCap Foaming Agents.

• **Improving Production Efficiencies**
OnCap Foaming Agents promote increased nucleation to reduce cooling times and thereby reduce production cycle times.
• **Helping Customers Grow**
Many industries are required to reduce the weight of their products because of government mandates or just a desire to reduce shipping costs. OnCap Foaming Agents help customers achieve these goals.
• **Reduces scrap caused by sink marks or unfilled areas of the products**
Less scrap results in increased profitability and competitiveness.

PolyOne's CFAs can effectively reduce the mass of plastic parts both with and without Class "A" surface finishes. For this study, however, the most significant advantage of CFAs is the former. Therefore, PolyOne's CFAs were applied to numerous Class "A" surface-finished plastic parts in this study. PolyOne Corporation provided generic feedback and advice regarding the amount of weight reduction feasible for plastic parts. These CFA application guidelines included considerations for a respective part's material, geometry, and application. In general, a 10% weight reduction was applied to parts for which a CFA was used. Higher mass reduction may be possible for many components, but would require a detailed analysis on the component and its use in order to safely apply such savings. Instead, a conservative estimate was applied based on PolyOne's expertise where parts' properties would not be adversely affected. For parts with a non-Class "A" surface finish, a weight reduction in the 20-30% range is possible.

The use of CFAs for light-weighting must be addressed on a part-by-part basis. Several variables must be taken into account for each component to understand the impact mass reduction will have on the final part's processing and performance. A feasibility breakdown provided by PolyOne is presented here, indicating guidelines and stipulations for the most common plastics used in the Chevrolet Silverado.

**20% Talc-filled Polypropylene (PP-GF20)**

- Talc can influence the success of the CFA. Based on the grade and particle size talc can improve cell size or potentially increase the rate of splay. The grain can help reduce the visual defects.
- Class "A" surface finish can be difficult to maintain. This will depend upon the geometry of and the gate location on the part.
- Potential weight reduction would be more in the 5-10% range at 1-3% LDR.
- Above 10% will begin to reduce the physical properties and affect the Class "A" surface finish.

- Due to polypropylene's shrinkage rate, the CFA will fill the cavity: weight loss is reduced due to the complete fill of the cavity.
- Aids in sink mark removal at lower 0.5-1% CFA loadings.
- PolyOne CFA CC10117068WE or CC10122763WE would be suggested for polypropylene.
- Surface texture can potentially hide the effects of a CFA so various grain options should be explored.

**Polycarbonate / Acrylonitrile Butadiene Styrene (PC/ABS)**

- This resin could achieve a 10-15% weight reduction. Careful selection of the proper CFA is required since the alloyed blends can have different ratios. Testing with the high heat CC10153776WE and CC10117068WE would be recommended.
- Class "A" surface finish can be difficult to maintain above 10%. This will depend upon the geometry of and the gate location on the part.
- Surface texture can potentially hide the effects of a CFA so various grain options should be explored.

**Polyamide 66 (PA66)**

- Processing with the high heat CFA CC10153776WE would be recommended.
- Class "A" surface finish can be difficult to maintain. This will depend upon the geometry of and the gate location on the part.
- Potential weight reduction would be more in the 5-10% range.
- Above 10% will begin to reduce the physical properties and affect the Class "A" surface finish.

**20% Glass-filled Polyamide (PA-GF20)**

- Processing with the high heat CFA CC10153776WE would be recommended.
- Glass will reduce the success of the CFA due to potential cell coalescence causing larger voids.
- Class "A" surface finish can be difficult to maintain. This will depend upon the geometry of and the gate location on the part.
- Potential weight reduction would be more in the 5-10% range.

- Above 10% will begin to reduce the physical properties and affect the Class “A” surface finish.

**15% Glass-filled / 25% Mineral-filled Polyamide 6 (15G/25M PA6)**

- Processing with the high heat CFA CC10153776WE would be recommended.
- Glass will reduce the success of the CFA due to potential cell coalescence causing larger voids.
- Class “A” surface finish can be difficult to maintain. This will depend upon the geometry of and the gate location on the part.
- Potential weight reduction would be more in the 5-10% range.
- Above 10% will begin to reduce the physical properties and affect the Class “A” surface finish.

**High-Density Polyethylene / Polypropylene (HDPE/PP)**

- This resin could achieve a 10-15% weight reduction. CC10117068WE and CC10122763WE are potential CFAs depending upon part geometry.
- Class A surface finish can be difficult to maintain above 10%. This will depend upon the geometry of and the gate location on the part.
- Surface texture can potentially hide the effects of a CFA so various grain options should be explored.
- Above 10% will begin to reduce the physical properties and affect the Class “A” surface finish.

PolyOne’s Chemical Foaming Agents are currently used in production in industrial housings and structural foam applications, and the automotive industry. Its CFAs are also currently used by many automotive OEMs.

In addition to PolyOne, some other ideas that were considered for weight reduction on the interior trim were 3M™ Glass Bubbles and the MuCell® process by Trexel. 3M Glass Bubbles are engineered hollow glass microspheres that are alternatives to conventional fillers and additives such as silicas, calcium carbonate, talc, and clay for many demanding applications. These low-density particles are used in a wide range of industries to reduce part weight, lower costs and enhance product properties.

The spherical shape of 3M Glass Bubbles offers a number of important benefits, including higher filler loading, lower viscosity/improved flow, and reduced shrinkage and warpage. It also helps the 3M Glass Bubbles blend readily into compounds, and makes them adaptable to a variety of production processes, including spraying, casting and molding. In addition, they offer greater survivability under demanding processing conditions, such as injection molding, and also produce stable voids, which results in low thermal conductivity and a low dielectric constant. The chemically stable soda-lime-borosilicate glass composition of 3M Glass Bubbles provides excellent water resistance, to create a more stable emulsion. They are also non-combustible and non-porous, so they do not absorb resin. And, their low alkalinity gives 3M Glass Bubbles compatibility with most resins, stable viscosity and long shelf life.

The MuCell microcellular foam injection molding process for thermoplastics materials provides unique design flexibility and cost savings opportunities not found in conventional injection molding. The MuCell process allows for plastic part design with material wall thickness optimized for functionality and not for the injection molding process. The combination of density reduction and design for functionality often results in material and weight savings. Suitable for recycling within the original polymer classification and allowing re-grind material to reenter the process flow.

The numerous cost and processing advantages have led to rapid global deployment of the MuCell process primarily in automotive, consumer electronics, medical device, packaging, and consumer goods applications.

#### 4.3.1.3 Summary of Mass Reduction Concepts Considered

**Table 4.3-4: Summary of Mass Reduction Concepts Initially Considered for the Interior Trim and Ornamentation Subsystem**

| Subsystem | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Interior Trim and Ornamentation Subsystem | | | |
| All plastic trim | Use Polyone® foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| All plastic trim | Use 3M glass bubbles | 8.55% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| All plastic trim | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |

#### 4.3.1.4 Selection of Mass Reduction Ideas

The mass reduction ideas selected for the Interior Trim and Ornamentation Subsystem were those to use the PolyOne foaming process for Class “A”-surfaced and Non-Class “A” surface parts for injection-molded parts. All PolyOne deductions are conservative at a 10% mass reduction per part. With proper engineering of the parts, however, up to 30% weight reduction may be achieved.

**Table 4.3-5: Mass Reduction Ideas Selected for the Interior Trim and Ornamentation Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **03** | **00** | **00** | **Body Group B** | |
| **03** | **05** | **00** | **Interior Trim and Ornamentation Subsystem** | |
| 03 | 05 | 05 | Front RH & LH Door Trim Panel | Use Polyone foaming agent |
| 03 | 05 | 06 | Rear Door or Rear Quarter Trim Panel | Use Polyone foaming agent |
| 03 | 05 | 07 | Pillar Trim Lower | Use Polyone foaming agent |
| 03 | 05 | 13 | Pillar Trim Upper | Use Polyone foaming agent |
| | | | | |

#### 4.3.1.5 Mass Reduction and Cost Impact Estimates

For the sub-subsystems, main floor trim, NVH pads, headliner assembly, sun visors and floor mats-OEM, no weight savings were taken. In the case of the headliner the electrical wiring weight can be reduced in another sub-subsystem.

**Table 4.3-6: Sub-Subsystem Mass Reduction and Cost Impact for Interior Trim and Ornamentation Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 03 | 05 | 00 | **Interior Trim and Ornamentation Subsystem** | | | | | | |
| 03 | 05 | 01 | Main Floor Trim | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 05 | 02 | NVH Pads | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 05 | 03 | Headliner Assembly | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 05 | 04 | Sun Visors | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 05 | 05 | Front RH & LH Door Trim Panel | | 0.843 | $2.06 | $2.44 | 8.55% | 0.03% |
| 03 | 05 | 06 | Rear Door or Rear Quarter Trim Panel | | 0.550 | $1.62 | $2.95 | 9.69% | 0.02% |
| 03 | 05 | 07 | Pillar Trim Lower | | 0.528 | $2.81 | $5.32 | 9.46% | 0.02% |
| 03 | 05 | 08 | Pillar Trim Upper | | 0.141 | $0.35 | $2.46 | 4.97% | 0.01% |
| 03 | 05 | 09 | Floor Mats - OEM | | 0.000 | $0.00 | -- | -- | 0.00% |
| | | | | **A** | **2.062** (Decrease) | **$6.84** (Decrease) | **$3.32** (Decrease) | **13.77%** | **0.08%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.3.2 Sound and Heat Control Subsystem

### 4.3.2.1 Subsystem Content Overview

As **Table 4.3-7** shows, the Sound and Heat Control Subsystem included the heat insulation shields – engine bay and underfloor; noise insulation – engine Bay and underfloor; heat shield – transmission; and heat shield – fuel tank.

**Table 4.3-7: Mass Breakdown by Sub-subsystem for the Sound and Heat Control Subsystem (Body)**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 03 | 06 | 00 | Sound and Heat Control Subsystem (Body) | |
| 03 | 06 | 01 | Heat Insulation Shields - Engine Bay & Underfloor | 0.899 |
| 03 | 06 | 02 | Noise Insulation, Engine Bay and Underfloor | 1.382 |
| 03 | 06 | 03 | Heat Shield - Transmission | 0.382 |
| 03 | 06 | 04 | Heat Shield - Fuel Tank | 2.121 |
| | | | | |
| | | | Total Subsystem Mass = | 4.784 |
| | | | Total System Mass = | 247.017 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 1.94% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.19% |

#### 4.3.2.2 Chevrolet Silverado Baseline Subsystem Technology

Due to the large amounts of heat given off by the engine, heat shields are used to protect components and bodywork from heat damage. Along with protection, effective heat shields can provide a performance benefit by reducing under-hood temperatures, therefore reducing the air intake temperatures. There are two main types of automotive heat shields: rigid and flexible. The rigid heat shields, once made from solid steel, are now often made from aluminum. Some high-end rigid heat shields are made out of aluminum sheet or other composites, with a thermal barrier, to improve the heat insulation. A flexible heat shielding is normally made from thin aluminum foils, sold either flat or in a roll, and is formed at installation. High-performance, flexible heat shields sometimes include extras, such as insulation. The Silverado has thin aluminum and steel heat shields. Therefore, no reduction was taken.

### 4.3.3 Sealing Subsystem

#### 4.3.3.1 Subsystem Content Overview

**Table 4.3-8** displays what is included in the Sealing Subsystem: Front Side Door Dynamic Weather-strip and Static Sealing.

**Table 4.3-8: Mass Breakdown by Sub-subsystem for the Sealing Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 03 | 07 | 00 | Sealing Subsystem | |
| 03 | 07 | 01 | Front Side Door Dynamic Weatherstrip | 4.897 |
| 03 | 07 | 02 | Static Sealing | 9.619 |
| | | | | |
| | | | Total Subsystem Mass = | 14.516 |
| | | | Total System Mass = | 247.017 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 5.88% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.59% |

#### 4.3.3.2 Chevrolet Silverado Baseline Subsystem Technology

The Silverado has typical sealing/weather-stripping. Automotive sealing/weather-stripping must endure extreme hot and cold temperatures, be resistant to automotive liquids such as oil, gasoline, and particularly windshield washer fluid, and must resist years of full sun exposure. Automotive sealing/weather-stripping is commonly made of EPDM, TPE, TPO polymers. **Image 4.3-6** shows the Chevrolet Silverado's door seal.

**Image 4.3-6: Chevrolet Silverado Door Seal**
*(Source: FEV, Inc.)*

#### 4.3.3.3 Mass Reduction Industry Trends

Mass reduction industry trends for sealing/weather-stripping show that TPE-v or TPV thermoplastic polyurethanes, thermoplastic co-polyester and thermoplastic polyamides can be used to replace EDPM. These materials are 10% to 25% lighter.

#### 4.3.3.4 Summary of Mass Reduction Concepts Considered

**Table 4.3-9** contains the ideas considered for mass reductions on the Sealing Subsystem.

**Table 4.3-9: Summary of Mass Reduction Concepts Initially Considered for the Sealing Subsystem**

| Subsystem | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **Sealing Subsystem** | | | |
| All seals | Combo Idea of TPV & PolyOne® | 32% Mass Reduction | TPV- faster cycle times, less capital equipment PolyOne- can do class "A" surface, No added capital cost |
| All seals | TPV | 25% Mass Reduction | TPV- faster cycle times, less capital equipment |
| All seals | Use Polyone® foaming agent | 10% Mass Reduction | Can do class "A" surface, No added capital cost |
| All seals | Use 3M glass bubbles | 8.55% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| All seals | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |

### 4.3.3.5 Selection of Mass Reduction Ideas

Jyco thermoplastic vulcanizates TPV weather-stripping materials and technologies were selected in consideration of weight savings and cost savings with a lighter, greener, cost effective product. **Figure 4.3-2** shows the TPV process foot print as compared to the EDPM process. It takes less energy to produce TPV then EDPM also less crap, labor, manufacturing and mold times as well as smaller line sizes and more environmentally friendly. Jyco supplies many different customers, such as General Motors, Volkswagen, Daimler, Volvo, and Daewoo.[41]

**A new, better material: TPV**. Jyco was founded by pioneers of seal design and processing technologies that have become industry standards. The Team was a multi year recipient of the GM *Supplier of the Year Award*, as well as top technology awards from other Fortune 50 industry leaders. Jyco was founded on the potential of a relative new material to weathersealing, a plastic-rubber compound known as thermoplastic vulcanizates (TPV). This material promised advantages over traditional thermoset rubbers: processing with the ease and economies of plastic, reducing weight and costs, yet performing as well or better than the EPDM rubber that dominated the weather sealing business. In 2000, TPV seals were being used by several Japanese and European OEMs, but the compound was virtually unknown to the North American automotive industry. From its inception, Jyco structured its manufacturing operations around state-of-the-art TPV processing equipment, By doing so, they avoided the capital burden, transitional pains, and retooling that other sealing suppliers face in adapting EPDM systems to processing TPV.

**Greener seals**: Unlike EPDM, TPV is recyclable. Production scrap can be directly reprocessed. The manufacturing process itself is free of VOCs and particulate emissions characteristic of EPDM processing.

**Nimbleness:** As a lean, technology-driven company with few layers at the top end – general managers and department heads report directly to the CEO and COO -- Jyco's nimble structure has always allowed the company to incorporate process improvements, respond to market changes, and develop new products with exceptional speed.

41 *All presentation information supplied by Jyco*

Lead by Jyco, TPV sealing systems quickly gained the interest of North American OEMs. Through innovations such as their own JyFlex™ TPV compound, product design and foam extrusions, Jyco's annual revenues increased an average of 55% per year between 2001 and 2007. Jyco had become a global leader in TPV sealing technology for the automotive, with joint venture operations in China, Europe and Latin America. The global automotive industry recognized Jyco as the only TPV supplier TS/ISO/16949/9000 certified for design, testing and manufacturing, as well as for innovations such as their JyGreen™ technology for recycling rubber automobile tires into high performance TPV sealing system. The Society of Plastics Engineers presented Jyco with their 2004 Environmental Innovation of the Year award. The Canadian Manufacturers & Exporters honored Jyco with the "Canadian Automotive Supplier Innovation" award in 2005. Frost & Sullivan has named JYCO the receipent of the 2009 North American Technology Innovation of the Year Award for Automotive Sealing Technologies.

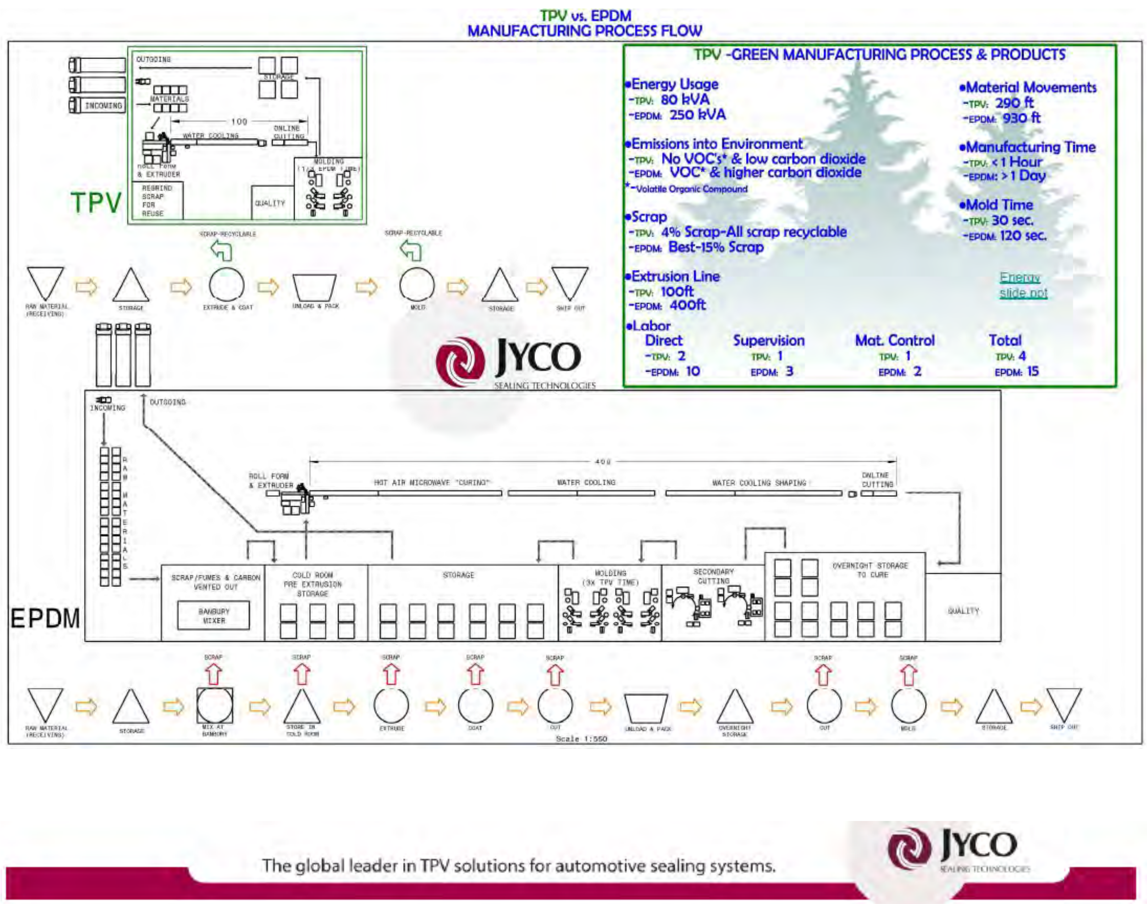



**Figure 4.3-2: Jyco TPV Footprint vs. EDPM**
*(Source:Presentation information supplied by Jyco)*

**Table 4.3-10: Mass Reduction Ideas Selected for the Sealing Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| 03 | 00 | 00 | **Body Group B** | |
| 03 | 07 | 00 | **Sealing Subsystem** | |
| 03 | 07 | 02 | Front Side Door Dynamic Weatherstrip | Combo, Replace EDPM with TPV & Use PolyOne foaming agent |
| 03 | 07 | 03 | Static Sealing | Combo, Replace EDPM with TPV & Use PolyOne foaming agent |
| | | | | |

#### 4.3.3.6 Mass Reduction and Cost Impact Estimates

**Table 4.3-11** shows the weight and cost savings per the Sealing Subsystem.

**Table 4.3-11: Sub-Subsystem Mass Reduction and Cost Impact for Sealing Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| 03 | 07 | 00 | **Sealing Subsystem** | | | | | | |
| 03 | 07 | 01 | Front Side Door Dynamic Weatherstrip | | 1.589 | $10.86 | $6.83 | 32.45% | 0.06% |
| 03 | 07 | 02 | Static Sealing | | 3.126 | $21.37 | $6.84 | 32.50% | 0.13% |
| | | | | | | | | | |
| | | | | A | 4.715 (Decrease) | $32.23 (Decrease) | $6.84 (Decrease) | 32.48% | 0.19% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.3.4 Seating Subsystem

#### 4.3.4.1 Subsystem Content Overview

**Table 4.3-12** shows the sub-subsystems included in the Seating Subsystem are the front driver seat, front passenger seat, rear 60% seat, rear 40% seat, and front center seat and console.

**Table 4.3-12: Mass Breakdown by Sub-subsystem for the Seating Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 03 | 10 | 00 | **Seating Subsystem** | |
| 03 | 10 | 01 | Seat Drivers Frt | 31.760 |
| 03 | 10 | 02 | Seat Passenger Frt | 26.770 |
| 03 | 10 | 03 | Rear 60% Seat | 25.862 |
| 03 | 10 | 04 | Rear 40% Seat | 17.241 |
| 03 | 10 | 05 | Frt center seat & console | 19.056 |
| | | | | |
| | | | **Total Subsystem Mass =** | **120.690** |
| | | | **Total System Mass =** | **247.017** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **48.86%** |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | **4.92%** |

### 4.3.4.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado front and rear seat frames are a complex array of stamped and welded parts to construct the back and bottom frames for all four seat groups. The foam is placed on the back and bottom frames over steel springs. The covering is then added over the foam. The covering can be made from number of different materials: cloth, leather, or a blend.

**Image 4.3-7** through **Image 4.3-14** show the front seats and frames for the Chevrolet Silverado.

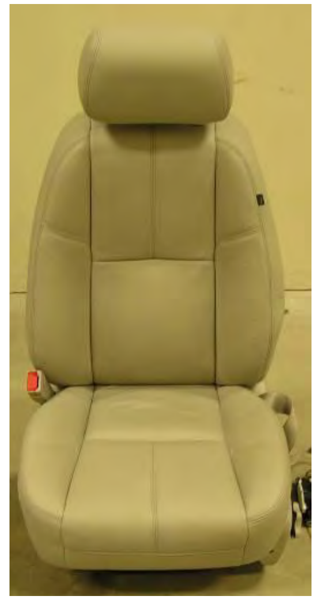


**Image 4.3-7 (Left): Front Seating with Center Console**

**Image 4.3-8 (Right): Front and Passenger Seats are Common**

*(Sources: FEV, Inc.)*

**Image 4.3-9: Front and Passenger Seat Back Frame**

*(Source: FEV, Inc.)*

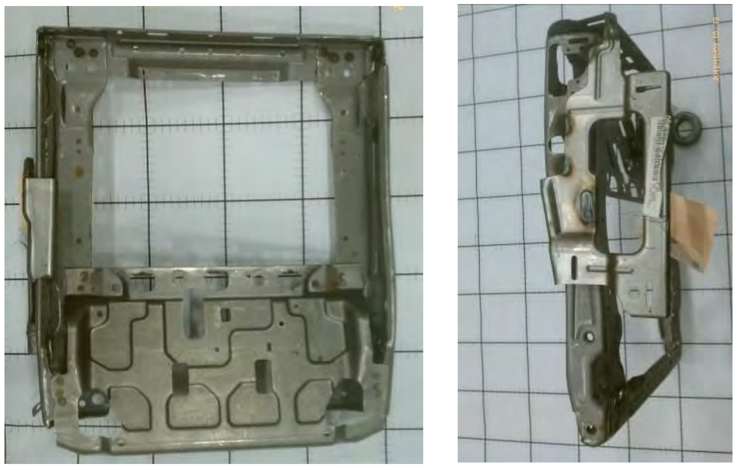


**Image 4.3-10: Front and Passenger Seat Bottom Frame**
*(Source: FEV, Inc.)*

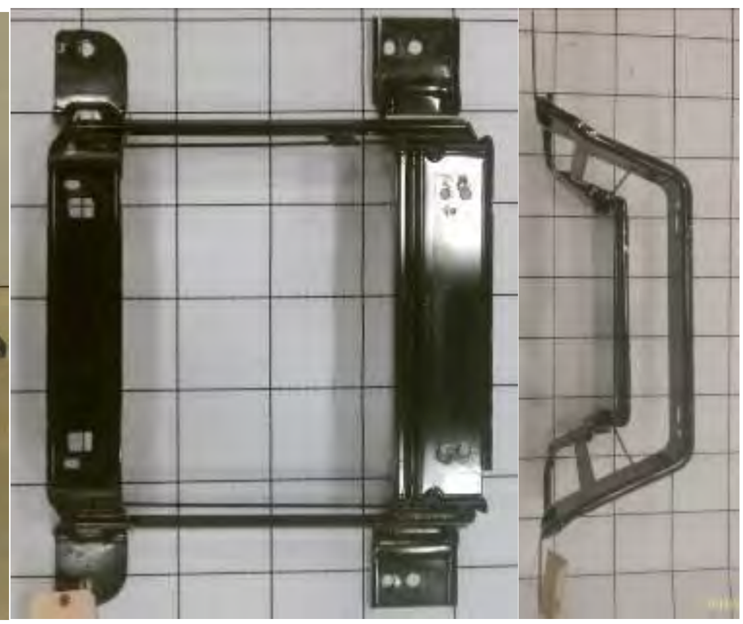



**Image 4.3-11 (Left): Front Center Console Seat**
*(Source: FEV, Inc.)*

**Image 4.3-12 (Right): Front Center Console Seat Floor Bracket**
*(Source: FEV, Inc.)*

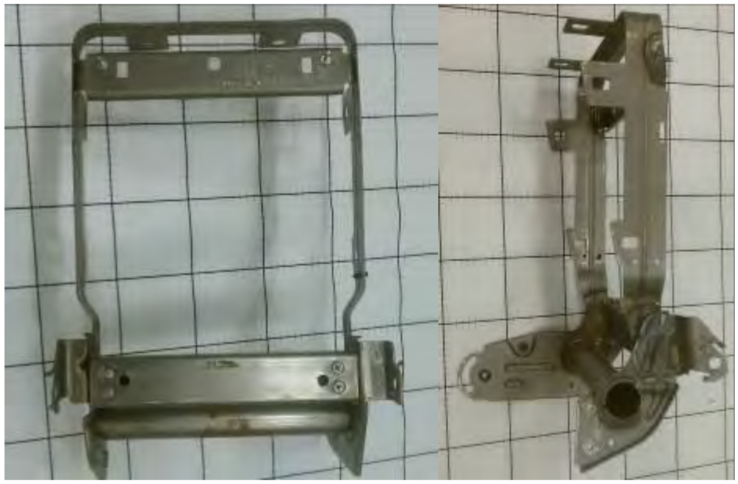


**Image 4.3-13: Front Center Console Seat Middle or Tub Bracket**
*(Source: FEV, Inc.)*

**Image 4.3-14: Front Center Console Seat Middle or Tub Cover Bracket**
*(Source: FEV, Inc.)*

The rear seat is split into two parts: the 60% portion is split to include the center arm rest section while the 40% portion composes the remainder of the rear seat.

**Image 4.3-15** through **Image 4.3-21** show the front seat and seat frames for the Chevrolet Silverado.


**Image 4.3-15: Rear 60% and 40% Seat**
*(Source: FEV, Inc.)*

**Image 4.3-16: Rear 60% Seat**
*(Source: FEV, Inc.)*

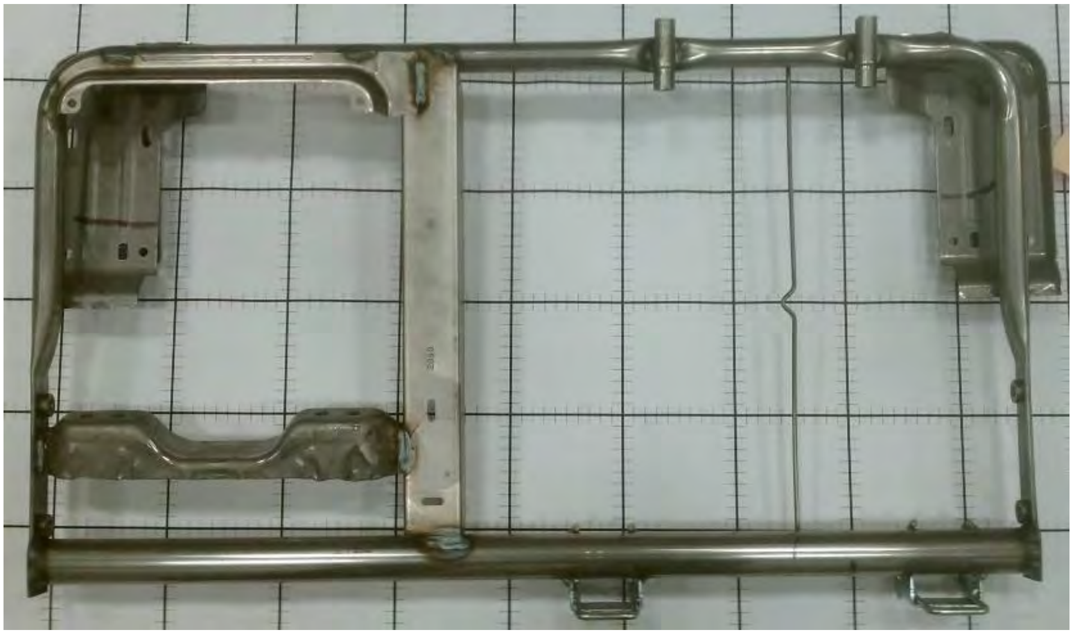


**Image 4.3-17: Rear 60% Seat Back Frame**
*(Source: FEV, Inc.)*

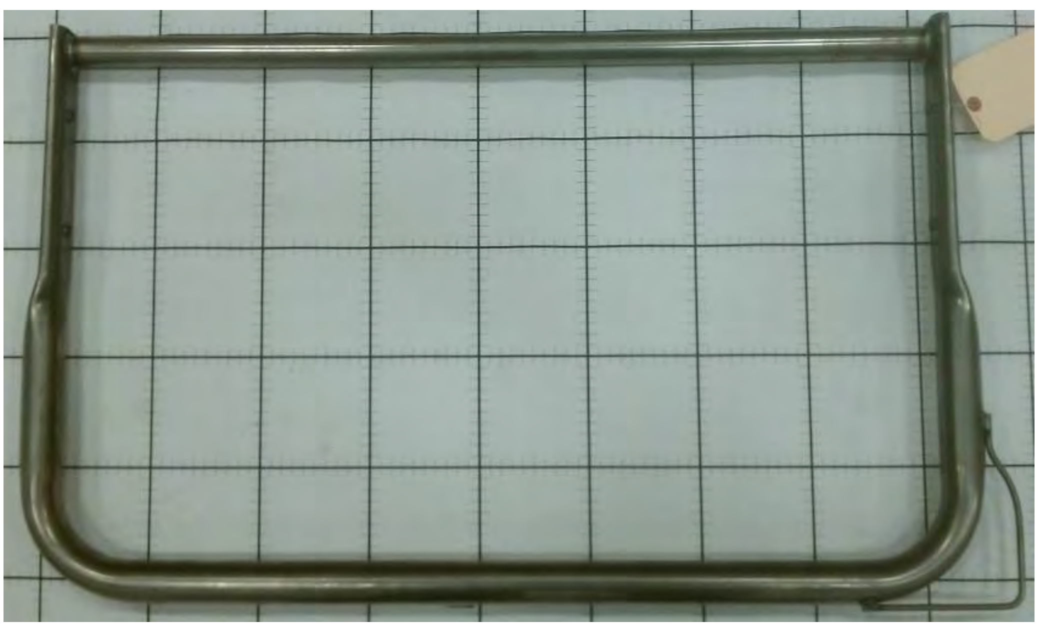


**Image 4.3-18: Rear 60% Seat Bottom Frame**
*(Source: FEV, Inc.)*

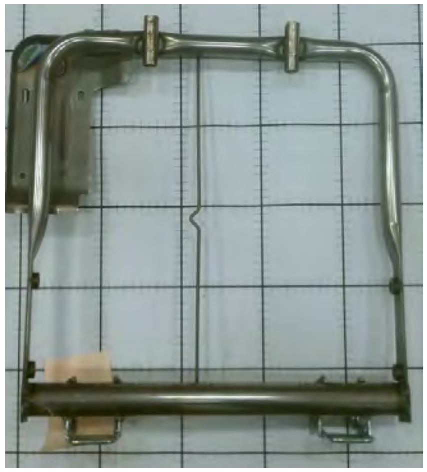




**Image 4.3-19 (Left): Rear 40% Seat**

**Image 4.3-20 (Center): Rear 40% Seat Back Frame**

**Image 4.3-21 (Right): Rear 40% Seat Bottom Frame**
*(Images 4.3-19 through 4.3-21 Source: FEV, Inc.)*

### 4.3.4.3 Mass Reduction Industry Trends

More and more emphasis is placed on reducing seat weight for that which they contribute to the overall vehicle, especially within the high weight of the frames. Therefore, many different types of seat frame constructions are emerging, such as those of high-strength steel, carbon fiber, plastics, cast magnesium, and aluminum. There are magnesium and plastic seat frames in some production vehicles today.

Some seat suppliers have been reluctant to the changeover for different reasons, such as a supplier that might have its own stamping facility and assembly equipment that has been paid for through many years of seat production, so to change over would be too costly. The cost fluctuation of plastic, magnesium and other lightweight materials are too volatile for some suppliers. Magnesium was more than $6.00 per kg in 2008, as low as $2.10 in 2007, and recently it has been $4.67. Also, some seat suppliers are not concerned with weight over cost. Carry-over seat construction is another reason that new technologies are not being used. The cost of design and testing can add considerable costs. Some OEMs are currently pulling seat planning in house to better control the design and build of lighter-weight seats. As new seat suppliers emerge with proven lightweight seat technologies and manufacturing methods, the thought process will again change.

Regarding the amount of attention seat frames have received in recent years as targets for weight reduction, this is largely due to all the stampings and weldings in the frames. This weight can be considerable, which is why new alternatives are being sought.

#### 4.3.4.4 Summary of Mass Reduction Concepts Considered

Reviewing the best option for removing seat frame mass, an in-depth study has to be done looking at current materials and processes. Plastic is less weight and cost, but up till now unproven for durability, safety, and overall performance. BASF® Plastics and Chemical Company has come up with a production plastic seat bottom and a tested seat back frame. Welded stamped and steel tube is proven, and is today's market mainstay. While it is lower in cost, it is not the best option for reducing weight. Welded stamped aluminum provides a good weight savings, but aluminum is expensive in comparison to alternative material selections and manufacturing costs. Cast aluminum offers the weight savings again, but not the best cost savings-to-weight ratio. Carbon fiber offers the best weight savings, but its availability and cost of material and manufacturing put this technology out of reach for the near-term. Cast magnesium offers a proven track record for durability and safety as well as considerable weight loss. Examples currently in production include the seat base/cushion supports on the Ford F150, Explorer and Flex.

Other ideas for seat weight reductions include using different types of foam for the seats, such as soy or pine wood. After reviewing these types of foam, however, it was determined that they did not provide a substantial weight savings. They also are not readily available for mass production. The costs of these materials are also very high. Their manufacturing process may actually add to greenhouse gas emissions, as well as being non-recyclable. Different types of manufacturing and welding were looked at as well for reducing weight and cost.

When analyzing the various options for seat mass reduction, the same solution was used for all the seat frames, using the Meridian die cast process. **Table 4.3-13** shows ideas considered.

**Table 4.3-13: Summary of Mass Reduction Concepts Initially Considered for the Seating Subsystem**

| Subsystem | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **Seating Subsystem** | | | |
| All plastic trim | Use Polyone® foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| All plastic trim | Use 3M glass bubbles | 6% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| All plastic trim | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Front & Pass seat | Use BASF® Plastic for both seat back and bottom frames | 50% Mass Reduction | Seat bottom is in production in an Opal vheical and the seat back has pass OEM testing |
| All steel welded seat frames | Die cast mag from Meridian® | 17 - 50% Mass Reduction | No stampings, no ecoat, no welding |
| Arm rest frame hinge RH & LH | Steel to Aluminum | 27% Mass Reduction | Cost more harder to stamp |
| All seating | Composite Seat frames ((Blow Mold)) | 25% Mass Reduction | Material cost more, tooling cost less, more testing then steel frames |
| All seating | Composite Seat Frame ((Carbon)) | 30% Mass Reduction | Material cost more, tooling cost less, more testing then steel frames, slower cycle times |
| All seating | Reduce size of recliner mechanism - use Lear EVO recliner | 20% Mass Reduction | smaller size, lighter weight |
| All seating | Use pine wood based foam | 10% Mass Reduction | High cost of material, short in supply |
| All seating | Use soy based foam | 10% Mass Reduction | High cost of material, short in supply |
| All seating | Dip seat springs - eliminate plastic protector | 5% Mass Reduction | Not all seats designed the same and might not apply, added process and cost |
| All seating | Eliminate foam backing on fabric | 10% Mass Reduction | Stiffer seat feel, degrade to original part |
| Rear | Hydro-form seat frame tubes | 10-15% Mass Reduction | High cost of tooling, unable to spot weld, high burden costs |
| all seats | Make seat frme out of Mag Thrixomold | 20-25% Mass Reduction | good proocity, fast cycle time, lower tooling cost |
| all seats | Cast aluminum frame | 15-20% Mass Reduction | Cost more for material, harder to weld |
| Arm rest | Use Alum. Sq.& round tube | 15-20% Mass Reduction | Cost more for material, harder to weld |
| Arm rest | Composite ((Blow Mold)) | 25% Mass Reduction | Material cost more, tooling cost less, more testing then steel frames |
| Arm rest | Composite ((Carbon)) | 30% Mass Reduction | Material cost more, tooling cost less, more testing then steel frames, slower cycle times |
| Arm rest | Make plastic | 25% Mass Reduction | higher cost in material, No welding needed, faster cycle time for manufacturing |
| Arm rest | Use AHSS on arm rest bracket | 10% Mass Reduction | higher cost in material, thinner materila could be used |
| Arm rest | Use lightening holes in arm rest bracket | 5% Mass Reduction | added punches in die, easy to implament |

### 4.3.4.5 Selection of Mass Reduction Ideas

**Table 4.3-14** contains the mass reduction ideas selected for the Seating Subsystem.

**Table 4.3-14: Mass Reduction Ideas Selected for the Seating Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 03 | 00 | 00 | Body Group B | |
| 03 | 10 | 00 | **Seating Subsystem** | |
| 03 | 10 | 01 | **Seat Drivers Frt** | |
| | | | Driver seat back frame | BASF® Plastic |
| | | | Driver seat bottom frame | BASF® Plastic |
| | | | Drivers seat trim | Use Polyone foaming agent |
| 03 | 10 | 02 | **Seat Passenger Frt.** | |
| | | | Passenger seat back frame | BASF® Plastic |
| | | | Passenger seat bottom frame | BASF® Plastic |
| | | | Passenger seat trim | Use Polyone foaming agent |
| 03 | 10 | 03 | **Rear 60% seat arm rest** | |
| | | | 60% Seat back frame | Meridian® Cast Magnesium |
| | | | 60% Seat bottom frame | Meridian® Cast Magnesium |
| | | | 60% Arm rest frame | Meridian® Cast Magnesium |
| | | | 60% Arm rest frame hinge RH & LH | Make out of Al |
| | | | 60% Seat trim | Use Polyone foaming agent |
| 03 | 10 | 04 | **Rear 40% seat back** | |
| | | | 40% Seat back frame | Meridian® Cast Magnesium |
| | | | 40% Seat bottom frame | Meridian® Cast Magnesium |
| | | | 40% Seat trim | Use Polyone foaming agent |
| 03 | 10 | 05 | **Frt Center Console** | |
| | | | Bottom frame | Meridian® Cast Magnesium |
| | | | Mid frame | Meridian® Cast Magnesium |
| | | | Seat frame | Meridian® Cast Magnesium |
| | | | Front center console trim | Use Polyone foaming agent |

Magnesium and plastic were chosen as the best options going forward in the study. Magnesium is a well-accepted material and many tier one suppliers use it in seat frame applications, such as the back frame of the rear 60/40 seat. Magnesium is the lightest structural material ($1.8 g/cm^3$), and is 75% lighter than steel and 33% lighter than aluminum. It is also the eighth most abundant element in the Earth's crust. Some other attributes behind the selection of magnesium include:

- High impact resistance
- High strength-to-weight ratio
- Can be cast and molded to net shape
- Excellent dimensional stability/repeatability
- 100% recyclable

There are two basic types of magnesium molding: Thixomolding® and die-casting. Thixomolding is a process of injection molding of magnesium chips as compared to plastic injection molding. It has certain limitations, such as size of the part, cost of the capital equipment, and availability of suppler to do larger parts.

One suppler in North America that has the equipment and the knowledge to do Thixomolded parts is Phillips Medisize. **Image 4.3-22** through **Image 4.3-24** show some of the Thixomolding equipment, products, and capabilities of Phillips Medisize.

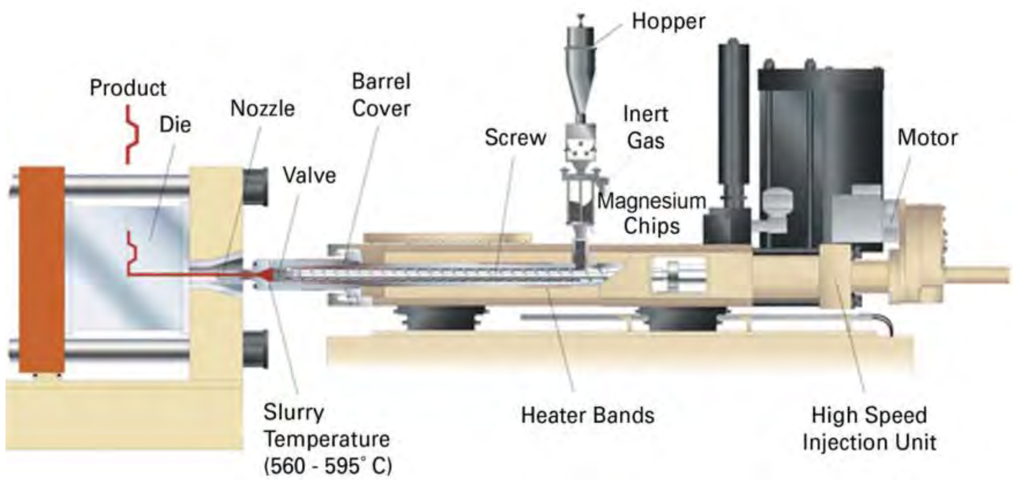



**Image 4.3-22: Thixomlding Machine Process**
*(Source: Phillips Medisize)*


**Image 4.3-23: Thixomolding Machine**
*(Source: Phillips Medisize)*

**Thixomolding Attributes**

- Complex parts with internal actions (lifters) more favorable
- Wall thicknesses of less than 0.100" more favorable
- Parts that require holding air pressure without leaking more favorable
- Tighter tolerances more favorable
- Parts with features requiring draft of less than one degree more favorable
- Molds are similar to plastic injection molding
- Trim dies are required
- Typical tooling will yield 150,000 cycles
- Molds provide superior surface finishes

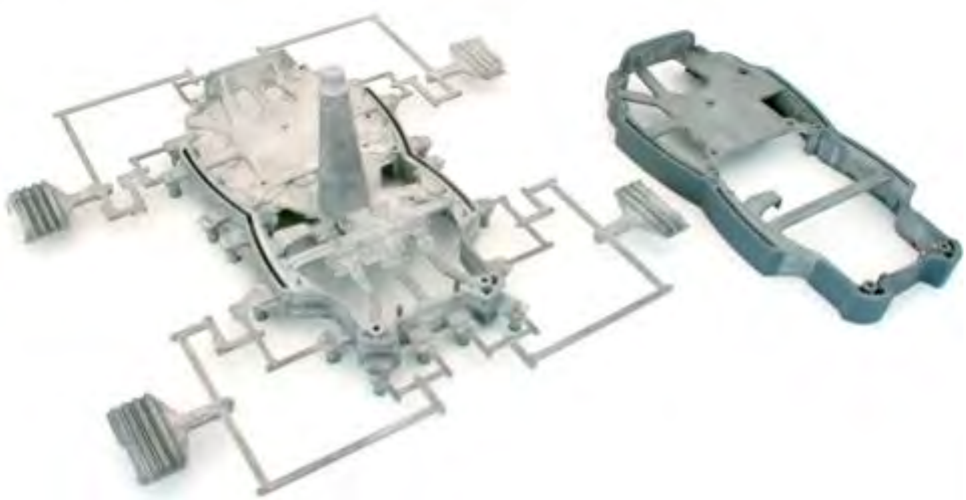


**Image 4.3-24: Thixomolding Part**
*(Source: Phillips Medisize)*

**Image 4.3-25** is a single-piece magnesium Lexus seat back created with the Thixomolding process.

**Image 4.3-25: Thixomolding Lexus Seat Back Example**
*(Source: Thixomolding)*

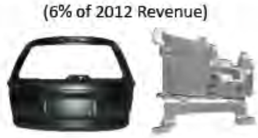
The other main type of magnesium processing is die casting. The largest magnesium diecast parts supplier in North America is Meridian®, which was consulted on the Silverado project to get the best possible outcome for cost and weight loss.

The die casting of magnesium is a process that Meridian has excelled in for years. Meridian is more than a die-casting company; they are driven to providing innovative and effective automotive solutions. The product offering is a result of the synergy created when the inherent properties of magnesium are combined with the design and manufacturing expertise of our global team. Some of Meridian's capabilities and qualifications include:

- Casting capability for aluminum and magnesium alloys
- The world's largest producer of magnesium components
- More than 30 years of experience assisting OEMs designing cost effective components
- Proven track record in successful launches of the most challenging die castings
- More than 1,600 dedicated employees
- More than 650,000 ft² of manufacturing space
- Fifty-six cold chamber die-casting machines from 500 to 4,000 tons
- More than 40,000 net metric tons of product shipped annually

Automobile manufacturers worldwide are increasingly turning to light-weight magnesium and magnesium alloy parts ways to reduce overall vehicle weight and improve fuel economy. OEMs have accelerated efforts for light-weighting to meet fuel economy targets. Meridian has a long-standing tradition of partnering with their OEM customers to develop innovative magnesium applications. Its product development team has introduced several structural magnesium "industry firsts," including the Ford F150 bolster, the Dodge Viper front of dash, the Lincoln MKT lift gate, and multiple GM instrument panels. **Table 4.3-15** shows some of the products manufactured by Meridian.

**Table 4.3-15: Cast Magnesium Products by Meridian**
*(All presentation material supplied by Meridian)*

| CORE PRODUCTS | COMPONENTS | SELECT PLATFORMS | |
|---|---|---|---|
| **INSTRUMENT PANELS**<br>(37% of 2012 Revenue)<br> | Instrument Panels<br>Front-of-Dash | GM Acadia, Traverse, Enclave<br>Cadillac CTS<br>Jeep Wrangler<br>GM Malibu<br>Range Rover Sport | Jaguar Sand X Type<br>Mercedes R Class<br>BMW Z3, Z4, X5, X6<br>Dodge Durango, Jeep Grand Cherokee |
| **POWERTRAIN**<br>(21% of 2012 Revenue)<br> | Transfer Cases<br>Oil Pans<br>Transmission Cases<br>Oil Fill Adaptors<br>Rear and Front Adapter Plates<br>Engine Mounts/Cradle | Ford F-Series, Expedition, Navigator<br>Honda 6-speed<br>Volkswagen 5-speed<br>Audi 5-speed<br>Nissan GTR | Mercedes 7-speed automatic<br>BMW N52 3.0L<br>Dodge Ram<br>Chevrolet Corvette<br>Cadillac CTS |
| **FECs & GORs**<br>(11% of 2012 Revenue)<br> | Front End Carriers<br>Grille Opening Reinforcements | Ford Super Duty<br>Ford F150<br>Lincoln MKT<br>Range Rover Sport<br>Volvo S60, V60 | Tesla Model S<br>Ford Flex |
| **Other**<br>(6% of 2012 Revenue)<br> | Liftgates<br>Engine Cradles<br>Spare Tire Carriers<br>Console/ Media Center Structures<br>Convertible Headers | Ford Mustang<br>Lincoln MKT<br>Ford Mondeo<br>Jeep Wrangler<br>Chrysler Vehicles | |
| **Bracketry**<br>(10% of 2012 Revenue)<br> | Pedals<br>Shifters<br>Roof Brackets<br>Steering Columns | GM Corvette<br>Honda Pilot<br>Audi 5-Speed<br>Ford F-Series, Expedition, Navigator<br>Dodge Ram | |
| **Seats**<br>(6% of 2012 Revenue)<br> | Front Seat Frames<br>Rear Seat Frames | Ford Explorer, Mountaineer, Flex<br>Ford F-Series, Expedition, Navigator<br>Lincoln MKT | |
| **Steering**<br>(6% of 2012 Revenue)<br> | Steering Wheels | Chrysler Platforms<br>Ford Fiesta | |

Cold chamber machines are used when the casting alloy cannot be used in hot-chamber machines. These include aluminum, zinc alloys with a large composition of aluminum, magnesium, and copper. The process for these machines starts with melting the metal in a separate furnace. Then a precise amount of molten metal is transported to the cold-chamber machine where it is fed into an unheated shot chamber (or injection cylinder). This shot is then driven into the die by a hydraulic or mechanical piston. This biggest disadvantage of this system is the slower cycle time due to the need to transfer the molten metal from the furnace to the cold-chamber machine.

**Figure 4.3-3** shows a schematic of a cold-chamber diecasting machine; **Image 4.3-26** is an actual cold chamber magnesium diecasting machine.

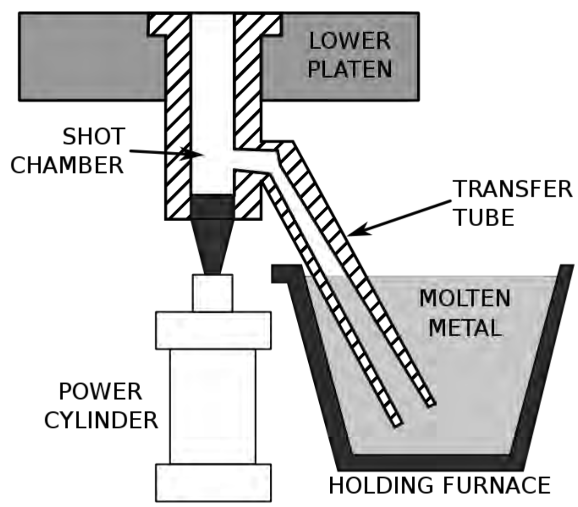



**Figure 4.3-3: Cold Chamber Magnesium Die Casting Machine**
*(Source: Google Images)*

**Image 4.3-26: Cold Chamber Magnesium Die Casting Machine**
*(Source: Wikimedia Commons)*

General Motors, in collaboration with Meridian Lightweight Technologies Inc., Strathroy, Ontario, Canada, and the Ohio State University in Columbus, Ohio, has won a $2.7 million Energy Department grant to explore magnesium die-casting technology. The project is intended to develop an integrated super-vacuum die-casting process using a new magnesium alloy to achieve 50% energy savings compared to the stamping and joining process currently used to manufacture car doors. By substituting steel inner panels with thin-walled magnesium castings, car doors could weigh 60% less, resulting in significant fuel economy improvements and carbon emission savings.

Meridian produced the 2013 GM Corvette seat back frame (**Image 4.3-27**) as well as seat frames and components for the Ford Explorer and Ford F150.

**Image 4.3-27: Concept of the GM Corvette Seat Back Frame**
*(Source: meridian-mag.com)*

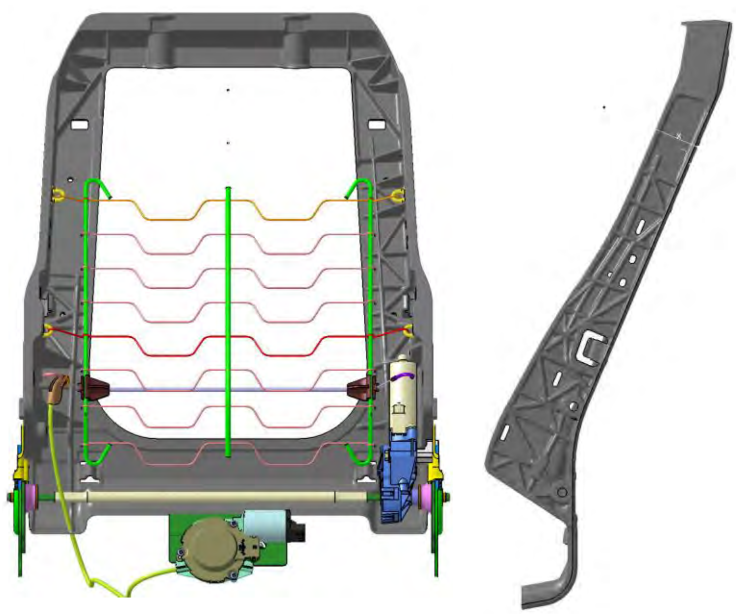


**Image 4.3-28: Concept of the Silverado Seat Back Frame**
*(Source: meridian-mag.com)*

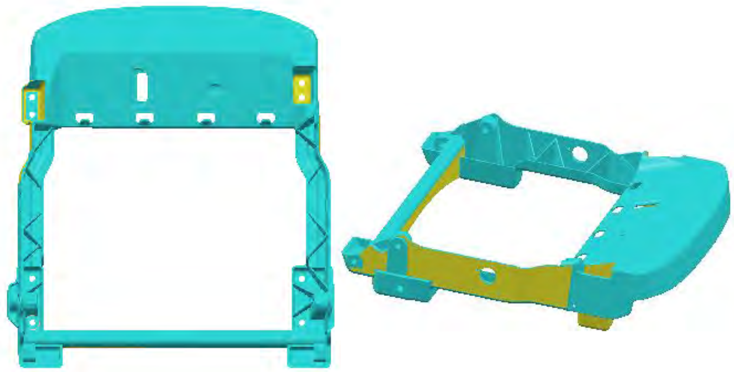


**Image 4.3-29: Concept of the Silverado Seat Bottom Frame**
*(Source: meridian-mag.com)*

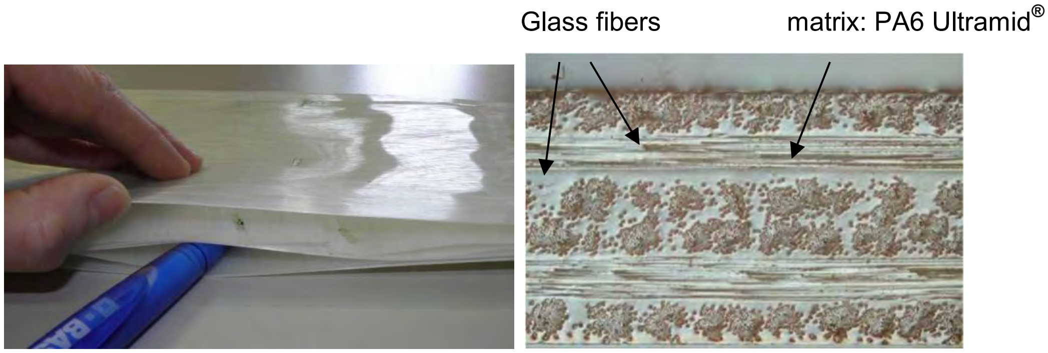
Magnesium is now the center of attention for the United States Automotive Materials Partnership (USAMP). This initiative investigates ways to develop a family car that can attain 2.9 L/100 km (80 mpg). The $10 million project involves the U.S. government, automakers, suppliers, universities, and national laboratories.[42]

Plastic was also used for the seat back and bottom frames in the front driver and passenger seats. BASF® has developed a continuous fiber reinforced plastic tape and laminate that has been put into production on an Opal Astra vehicle front seat bottom frame. BASF has also passed testing on this technology for the front seat back frames. This breakthrough has taken the weight and cut it half or more with incorporation of trim parts into the frame design. **Image 4.3-30** shows the Opal Astra bottom seat frame.

**Image 4.3-30: Opal Astra Seat Bottom Frame Using the BASF Laminate**
*(Source: BASF)*

42 *Source: Magnesium.com/data-bank*

The laminate is made up of four, .25 mm layers of glass fibers and a matrix of PA6 Ultramid® that are consolidated into a tape or laminate. **Image 4.3-31** shows before and after the consolidation.




**Before Consolidation** **After Consolidation**

**Image 4.3-31: BASF Laminate**
*(Source: BASF)*

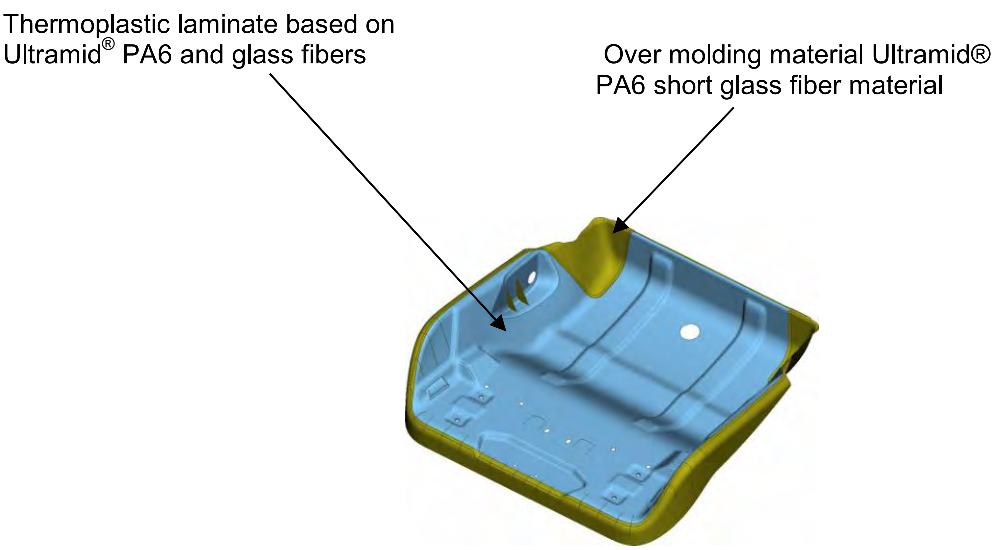



**Image 4.3-32: Opal Astra Front Seat Pan**
*(Source: BASF)*

**Image 4.3-33** shows the open injection mold tool with a piece of BASF laminate being heated by an infrared (IR) heater.

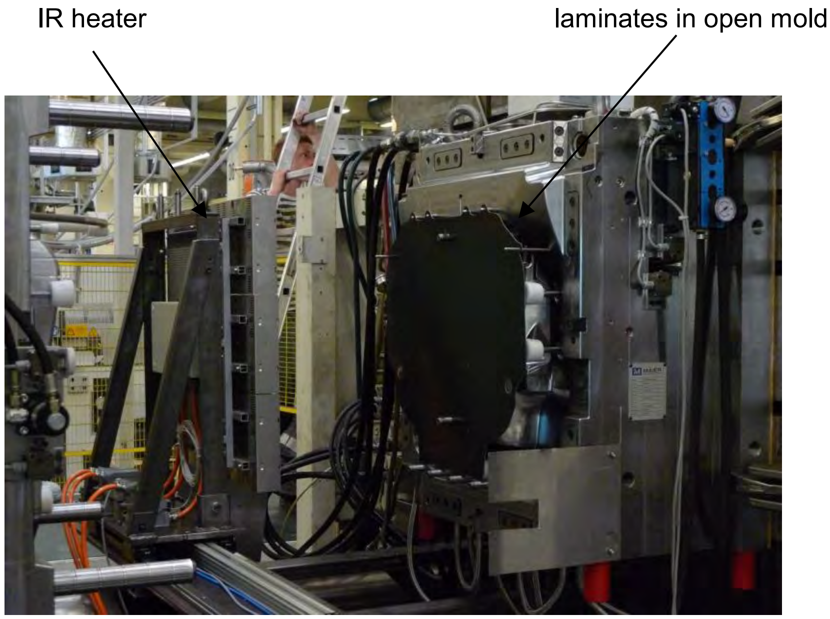



**Image 4.3-33: Injection Molding Operation with BASF Laminate**
*(Source: BASF)*

BASF has used the laminate on the seat pan and the tape for applications on the seat back frame (**Image 4.3-34** and **Image 4.3-35**). The tapes are used for parts with areas of highest local anisotropic load distribution (e.g., front seat back rests and the laminates are used for predominantly closed areas, mechanical load rather evenly distributed e.g. seat pans, rear seat backrests, vehicle floors. The advanced tapes and laminates can also be used for structural automotive parts such as roof cross member, cross car beam, crash extensions, fire wall, front end, structural floor, battery integration, and structural inserts in the pillars and roof frame.


**Image 4.3-34: Laminate and Tape Applications**
*(Source: BASF)*

**Image 4.3-35** is an example of a prototype seat backrest with over molded tape reinforcement. The seat back frame is not in production at this time, but has passed OEM testing and will be launched into production in the near future.

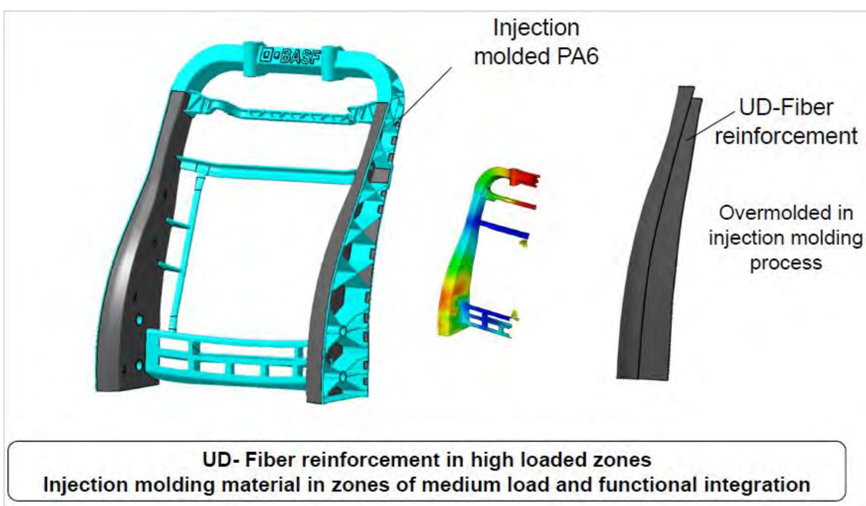



**Image 4.3-35: Prototype-Seat Backrest with Over-Molded Tape Reinforcement Example**
*(Source: BASF)*

The BASF Continuous Fiber Reinforced Engineering Plastics offer great weight savings. With the injection molding process and added integrated parts into the frame over conventional seat processing of multiple stampings and weldings, it can be a cost wash or savings. Some considerations on the composites include:

- Thermoplastic composites have potential to replace automotive structural parts
- Design tools are available for the development of bespoke composite designs
- Indications are a 33% or more weight save in the case of a whole front seat assembly
- The weight save provides an overall environmental advantage compared to steel
- Thermoplastic composites have potential to be produced via volume processes
- Costs are between Carbon Fiber and Steel, less with part integration
- Form and performance capabilities are good, stable and repeatable
- Composites enable "thin seat" styling cues and improved vehicle packaging

**Table 4.3-16: Mass Reduction and Cost Impact for the Seating Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 03 | 10 | 00 | Seating Subsystem | | | | | | |
| 03 | 10 | 01 | Seat Drivers Frt | | 3.107 | -$15.00 | -$4.83 | 9.78% | 0.13% |
| 03 | 10 | 02 | Seat Passenger Frt | | 3.096 | -$15.36 | -$4.96 | 11.56% | 0.13% |
| 03 | 10 | 03 | Rear 60% Seat | | 5.553 | -$43.73 | -$7.88 | 21.47% | 0.23% |
| 03 | 10 | 04 | Rear 40% Seat | | 3.350 | -$23.87 | -$7.13 | 19.43% | 0.14% |
| 03 | 10 | 05 | Frt center seat & console | | 4.053 | -$29.93 | -$7.38 | 21.27% | 0.17% |
| | | | | X | 19.159 (Decrease) | -$127.89 (Increase) | -$6.68 (Increase) | 15.87% | 0.78% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.3.5 Instrument Panel and Console Subsystem

#### 4.3.5.1 Subsystem Content Overview

As seen in **Table 4.3-17**, the Instrument Panel and Console Subsystem has five sub-subsystems containing mass. The primary ones are the Cross-Car Beam (CCB), Instrument Panel Main Molding, and Closure Panel or Knee Bolster, Applied Decorative Trim, and Switch Pack-Instrument Panel Sub-subsystems. The CCB includes the beam and all welded brackets. It serves as the primary mounting structure for all Instrument Panel sub-assemblies and modules like the HVAC main unit, radio, glove box, center stack, and steering wheel. The instrument panel main molding includes the instrument panel trim and other plastic covers and structural components that surround the dash.

**Table 4.3-17: Mass Breakdown by Sub-subsystem for the Instrument Panel and Console Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 12 | 00 | **Instrument Panel and Console Subsystem** | |
| 03 | 12 | 01 | Cross-Car Beam (IP) | 11.923 |
| 03 | 12 | 02 | Instrument Panel Main Molding | 7.215 |
| 03 | 12 | 03 | Closure Panel or Knee Bolster - (IP) | 6.936 |
| 03 | 12 | 04 | Applied Decorative Trim - (IP) | 2.804 |
| 03 | 12 | 05 | Switch Pack - Instrument Panel (IP) | 1.959 |
| | | | **Total Subsystem Mass =** | **30.837** |
| | | | **Total System Mass =** | **247.017** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **12.48%** |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | **1.26%** |

#### 4.3.5.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado has a traditional instrument panel assembly (**Image 4.3-36**) with a steel CCB that has welded brackets and fixtures (**Image 4.3-37**). Components are mostly welded together with some use of fasteners.

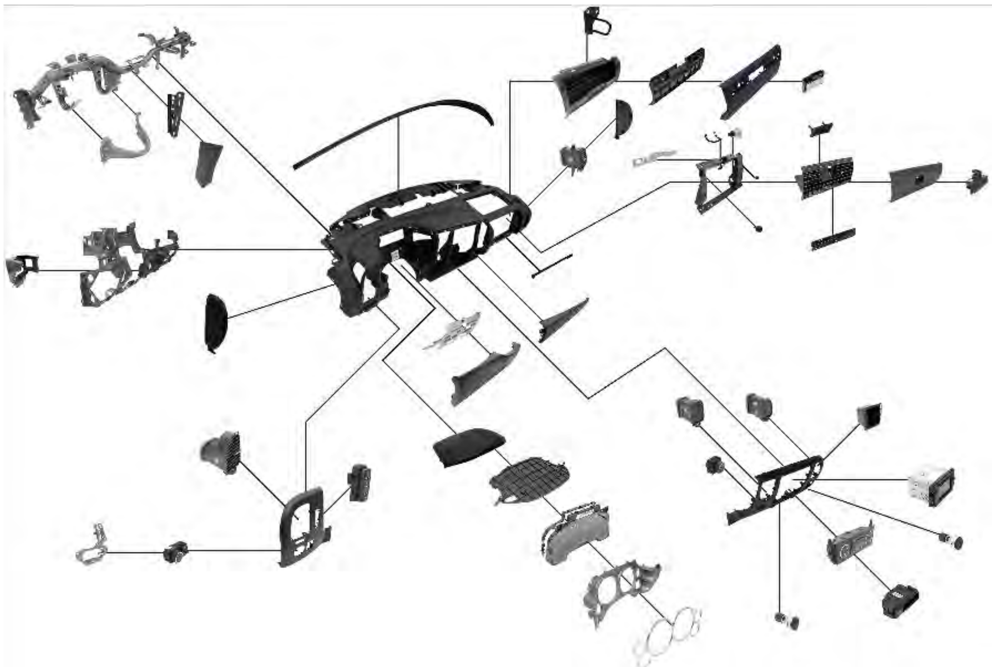


**Image 4.3-36: Chevrolet Silverado Dash Assembly**
*(Source: A2mac1 database)*

**Image 4.3-37: Chevrolet Silverado Cross-Car Beam**
*(Source: FEV, Inc.)*

The instrument panel base dash, shown in **Image 4.3-38** is a polypropylene and polyethylene talc-filled blend. The dash inner support is pictured in **Image 4.3-39**.

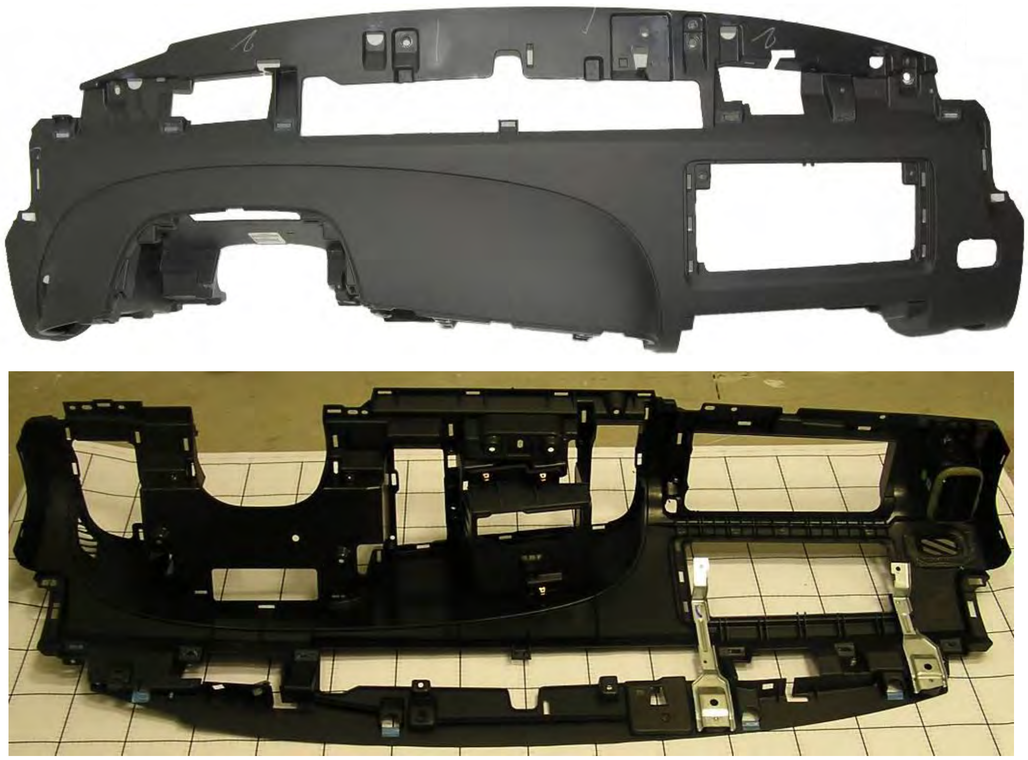


**Image 4.3-38: Top of Dash, IP Base with Skin Cover**
*(Source: FEV, Inc.)*

**Image 4.3-39: Dash, Inner Support**
*(Source: FEV, Inc.)*

The instrument panel included the entire dash assembly along with the inner support and the outer dash skin. The dash contained several storage compartments, cup holders, and accessory power outlets. While the center stack had some non-Class "A" parts made of ABS, it is mostly composed of Class "A" surface parts made of talc-filled PP or nylon.

#### 4.3.5.3 Mass reduction Industry Trends

The most notable opportunity for light-weighting the Instrument Panel Subsystem is with the CCB. There are a variety of light-weighting technologies and ideas being applied to

CCBs throughout the industry. Traditionally, CCBs have been rolled steel products, but this is starting to transform. Mubea, Inc. is a company that specializes in Tailor Rolled Products. They use specialty rolling equipment that varies the thickness of a single piece so that thick sections are only applied where structurally necessary (**Figure 4.3-4**) other sections of the same beam are manufactured to be thinner, thus saving weight compared to a traditional CCB. Utilizing this technology not only saves weight, but the reduced raw material cost will offset the additional processing cost, resulting in a near cost-neutral exchange. Tailor Rolled Beams are currently used on the CCBs of BMW's 1-, 3-, 5-, and 7-Series vehicles.

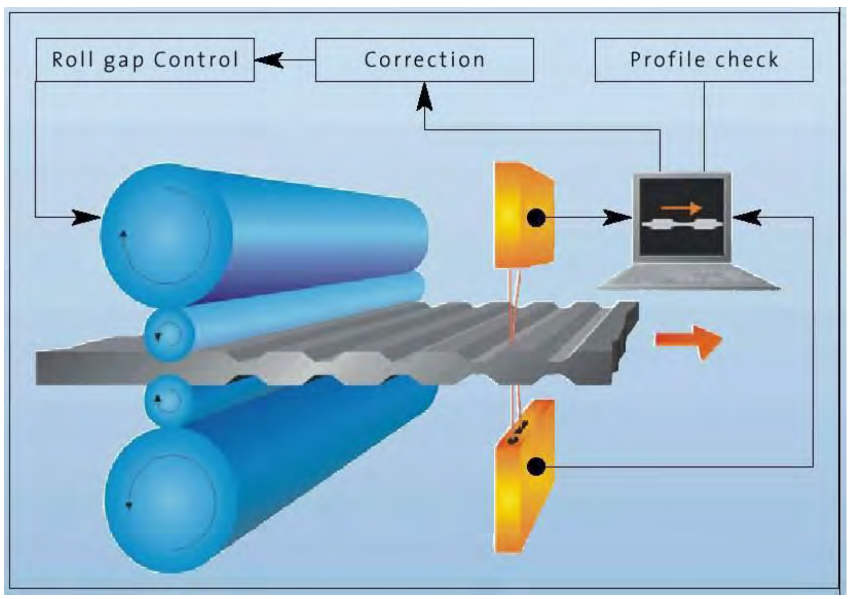
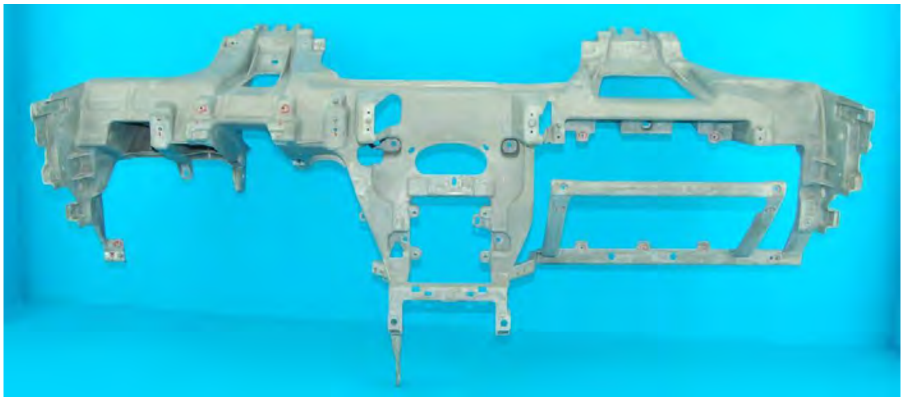
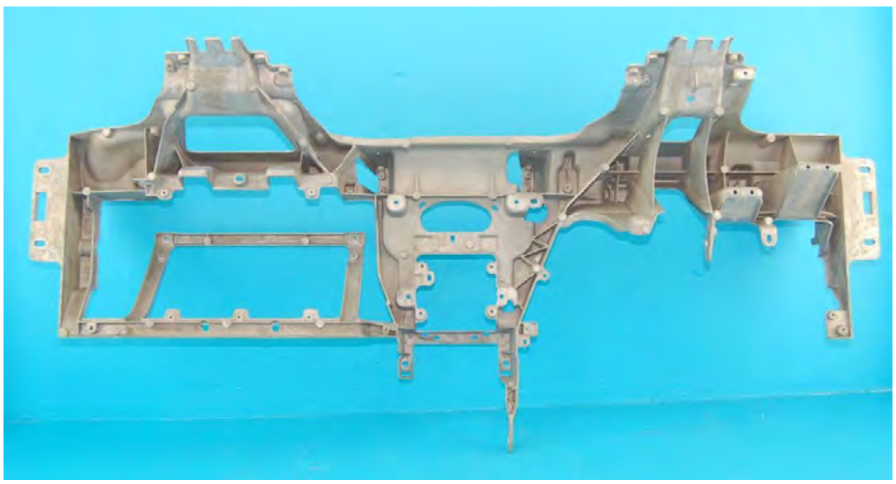



**Figure 4.3-4: Illustration of Mubea's Tailor Rolled Blank Process**
*(Source: Mubea http://www.stahl.karosserie-netzwerk.info/59.htm)*

Automakers have also begun using alternative materials on cross-car beams. These include the use of both aluminum and magnesium. The McLaren MP4-12C uses aluminum CCBs, and the Jaguar XKR, BMW X5, and BMW X6 all use magnesium. Chrysler has also embraced non-ferrous CCBs, using magnesium in the Dodge Caliber and on numerous Jeep models. The magnesium CCB from the 2010 Dodge Caliber 2.4 R/T is shown in **Image 4.3-40**. This magnesium beam differs significantly in design and manufacturing process than the baseline Silverado cross-car beam in **Image 4.3-37**. The magnesium beam is a single-piece, diecast component, while the steel beam is a multi-piece, rolled, stamped, and welded assembly.



(a) Front View



(b) Back View

**Image 4.3-40: Dodge Caliber Magnesium Cross-Car Beam**

*(Source: A2mac1 http://www.a2mac1.com/Autoreverse/reversepart.asp?productid=150&clientid=1&producttype=2)*

The Stolfig® Group in Europe conducted a comparison of three CCBs, as shown in **Image 4.3-41**. The weight savings associated with aluminum and magnesium beams compared to steel is immediately apparent, but of course this mass reduction is not without a cost penalty.

Material: Steel
Thickness: 1.0 mm
Mass: 8.54 kg

Material: Aluminum
Thickness: 1.5 mm
Mass: 4.41 kg

Material: Magnesium
Thickness: 1.7 mm
Mass: 3.22 kg

**Image 4.3-41: CCB Examples Compared by the Stolfig Group**
*(Source: Stolfig http://www.stolfig.com/lang/en/services/carbeam.php)*

In the plastic components that make up the Instrument Panel Subsystem, PolyOne's Chemical Foaming Agents (CFAs) are capable of reducing the mass of plastic components while maintaining the Class "A" surface finish. PolyOne technology is currently used in production in industrial housings and structural foam applications as introduced in **Section 4.3.** SABIC® is a materials supplier with much of their focus on plastics. They are one of the largest plastics suppliers in the world and provided numerous mass reduction ideas across all systems of the vehicle, one of which is the Instrument Panel Subsystem. SABIC's long glass fiber polypropylene (LGF-PP) Stamax® is a material used on instrument panels to maintain rigidity requirements while also reducing weight. According to SABIC, a mass reduction of 30% is attainable as the use of LGF-PP allows the wall thickness of the Instrument Panel Dash Base to be reduced to 2 mm. The rigidity is maintained over a wide temperature range. Instrument Panel thicknesses as thin as 1.8 mm are currently in production. LGF-PP has a higher modulus than talc-filled PP, and the use of advanced engineering simulation (Autodesk® Moldflow® software) and FEA allow SABIC to achieve such mass reduction.

#### 4.3.5.4 Summary of Mass Reduction Concepts Considered

Ideas that were considered to reduce the Instrument Panel Subsystem mass are compiled in **Table 4.3-18**.

**Table 4.3-18: Summary of Mass Reduction Concepts Initially Considered for the Instrument Panel Subsystem**

| Subsystem | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **IP Subsystem** | | | |
| All plastic trim | Use Polyone® foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| All plastic trim | Use 3M glass bubbles | 6% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| All plastic trim | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| IP | Make IP frame out of Mag Thrixomold | 40-50% Mass Reduction | good proocity, fast cycle time, lower tooling cost |
| IP | Cast aluminum | 20-30% Mass Reduction | Cost more for material, harder to weld |
| IP | Cast mag. ((High Pressure Die Cast)) | 40-50% Mass Reduction | No stampings, no ecoat, no welding |
| IP | Use Alum. Sq.& round tube | 15-20% Mass Reduction | Cost more for material, harder to weld |
| Knee Bolster Reinforcement brkt | Steel to plastic | 56% Mass Reduction | Less tooling, weight loss |

#### 4.3.5.5 Selection of Mass Reduction Ideas

The sub-subsystems to which mass reduction ideas were applied are shown in **Table 4.3-19**. Magnesium was selected to be used for the CCB. While high in material cost, magnesium offers a substantial weight savings and, after evaluation, was favorable to the aluminum CCB. Magnesium beams are also in current use by multiple OEMs. The multi-piece steel CCB was reduced to a two-component assembly with the magnesium beam. The magnesium beam was manufactured using die casting by Meridian®, which lends itself to component integration.

PolyOne's CFAs were applied to eligible plastic parts resulting in a 10% mass reduction per part. PolyOne technology is currently used in production in industrial housings and structural foam applications, as introduced in **Section 4.3**.

**Table 4.3-19: Mass Reduction Ideas Selected for Detail Analysis of the Instrument Panel and Console Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| 03 | 00 | 00 | **Body Group B** | |
| 03 | 12 | 00 | **Inst. Panel & Console** | |
| | | | | |
| 03 | 12 | 01 | **Cross Car Beam (IP)** | |
| | | | Cross Car Beam | Cast Magnesium |
| | | | Cross Car Beam to Floor Brkt Cover | Use Polyone foaming agent |
| | | | | |
| | | | | |
| 03 | 12 | 03 | **Instrument Panel Main Molding** | |
| | | | Instrument Panel Main Molding trim | Use Polyone foaming agent |
| | | | | |
| | | | | |
| 03 | 12 | 04 | **Closure Panel or Knee Bolster - (IP)** | |
| | | | Closure Panel or Knee Bolster - (IP) trim | Use Polyone foaming agent |
| | | | Knee Bolster Reinforcement brkt | Combo: Steel to plastic & Polyone foaming agent |
| | | | | |
| | | | | |
| 03 | 12 | 05 | **Applied Decorative Trim - (IP)** | |
| | | | Applied Decorative Trim - (IP) trim | Use Polyone foaming agent |
| | | | | |
| | | | | |

### 4.3.5.6 Mass Reduction and Cost Impact Results

**Table 4.3-20** shows the weight savings for the ideas applied to the Instrument Panel and other sub-subsystem as well as their cost impact. As seen in the first line of this table, the magnesium CCB generates a cost increase of $38.15 and saves approximately 5.453 kg.

**Table 4.3-20: Mass Reduction and Cost Impact for the Instrument Panel and Console Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Net Value of Mass Reduction Idea | | | | |
| 03 | 12 | 00 | **Instrument Panel and Console Subsystem** | | | | | | |
| 03 | 12 | 01 | Cross-Car Beam (IP) | | 5.453 | -$38.15 | -$7.00 | 45.74% | 0.22% |
| 03 | 12 | 02 | Instrument Panel Main Molding | | 0.535 | $1.40 | $2.61 | 7.41% | 0.02% |
| 03 | 12 | 03 | Closure Panel or Knee Bolster - (IP) | | 0.664 | $1.01 | $1.53 | 9.57% | 0.03% |
| 03 | 12 | 04 | Applied Decorative Trim - (IP) | | 0.136 | $0.25 | $1.86 | 4.84% | 0.01% |
| 03 | 12 | 05 | Switch Pack - Instrument Panel (IP) | | 0.037 | $0.20 | $5.38 | 1.88% | 0.00% |
| | | | | X | 6.824 (Decrease) | -$35.29 (Increase) | -$5.17 (Increase) | 22.13% | 0.28% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.3.6 Occupant Restraining Device Subsystem

#### 4.3.6.1 Subsystem Content Overview

The Occupant Restraining Device Subsystem breakdown and mass is shown in **Table 4.3-21**. The seat belt restraints did not have any mass reduced and were assumed to remain unchanged going from the baseline to the redesign. An engineering analysis may have to be performed on the seat belt reaction time for the new vehicle due to its overall reduction in mass and different response to a crash, but such an investigation was beyond the scope of this study.

**Table 4.3-21: Mass Breakdown by Sub-subsystem for the Occupant Restraining Device Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 03 | 20 | 00 | Occupant Restraining Device Subsystem | |
| 03 | 20 | 01 | Seat Belt Assembly Front Row | 3.961 |
| 03 | 20 | 03 | Passenger Airbag / Cover Unit | 4.028 |
| 03 | 20 | 06 | Restraint Electronics | 0.798 |
| 03 | 20 | 08 | Seat Belts - Second Row | 3.998 |
| 03 | 20 | 12 | Curtain Airbag System | 5.012 |
| 03 | 20 | 15 | Tether Anchorages - Non Integrated | 0.462 |
| 03 | 20 | 18 | Steering Wheel Airbag | 1.386 |
| | | | | |
| | | | Total Subsystem Mass = | 19.645 |
| | | | Total System Mass = | 247.017 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 7.95% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.80% |

### 4.3.6.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado represents a conservative approach to the design of the airbag modules. In **Image 4.3-42**, the passenger side airbag is seen mounted to the IP. Steel is used for nearly all of the housings and brackets as shown for the passenger airbag housings in **Image 4.3-43**. The airbag material itself is a standard nylon fabric (used on most airbags in the industry) and dual-stage airbag inflators are used. As a result of the metal housings used in the baseline steering wheel airbag, numerous fasteners are necessary to assemble components together as shown in **Image 4.3-44**. These include screws, rivets, studs, nuts, and springs.

**Image 4.3-42: Silverado IP with Mounted Passenger Airbag**
*(Source: A2mac1 database)*

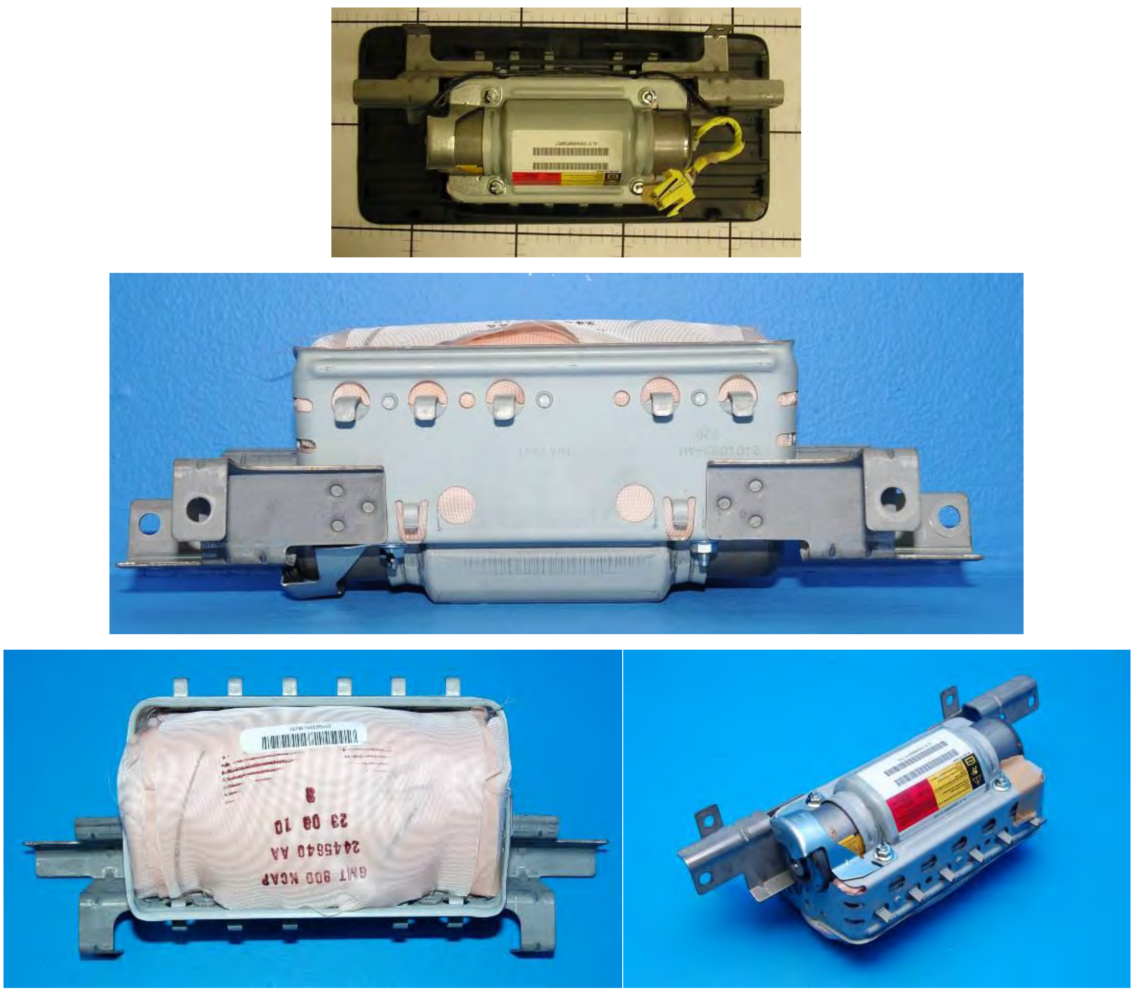


**Image 4.3-43: Silverado Passenger Airbag**
*(Source: A2mac1 database and FEV, Inc.)*


**Image 4.3-44: Silverado Steering Wheel Airbag Assembly and Various Fasteners**
*(Source: A2mac1 database)*

### 4.3.6.3 Mass Reduction Industry Trends

Plastic airbag housings are used on many high volume vehicle applications. DSM Engineering Plastics is a global plastics supplier and specializes in metal to plastic replacements in automotive applications. Their Akulon® products, glass fiber reinforced glass-filled polyamide, have been used on many driver and passenger air bag housings for all of the domestic OEMs over the last 10 years. An example of steel to plastic airbag housing is shown in **Image 4.3-45**. As seen, the design remains quite similar when changed from a multi-piece steel unit to a single-piece injection-molded housing. This allows for easy integration into an existing product line. **Image 4.3-46** displays a conventional stamped steel airbag housing next to a plastic injection molded housing. This resemblance reinforces the applicability of a plastic injection molded airbag for the Silverado.

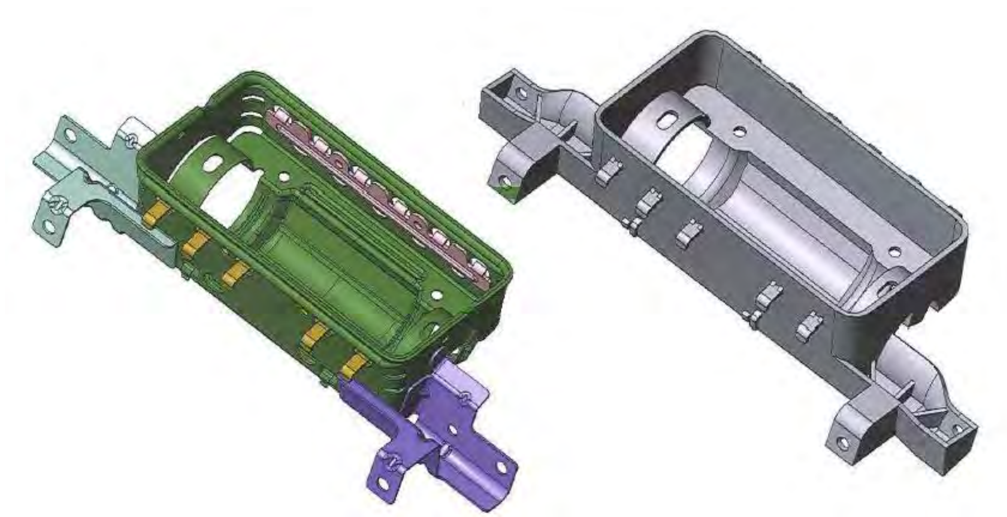


**Image 4.3-45: Passenger Side Airbag Housings, Fabricated Steel Assembly (left) and Injection Molded Plastic Component (right)**
*(Source: Images Courtesy of DSM Engineering Plastics and Takata)*

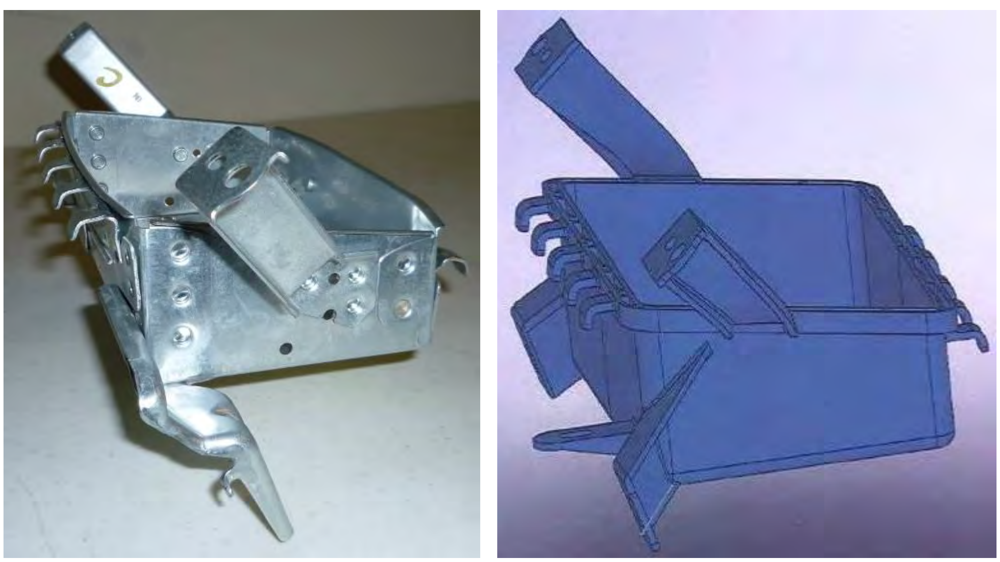


**Image 4.3-46: Airbag Housing (left) and Plastic Airbag Housing Rendering (right)**
*(Sources: [Left] FEV, Inc., [Right] Courtesy of DSM Engineering Plastics)*

Takata Corporation, a leading global supplier of automotive safety systems, provided significant mass reduction ideas for the airbag modules for this study. The most innovative of which was its Vacuum Folding Technology (VFT). VFT is a process that allows the bags to be packed much more tightly than airbags traditionally have been by pulling a vacuum during its packaging. The surrounding components (housings, covers, etc.) can then be made smaller and, therefore, with lighter weight. A size reduction of 30-

60% is typically observed accompanied by a mass reduction of around 20-35%. A size comparison of a standard airbag module versus a VFT is illustrated in **Image 4.3-47**.

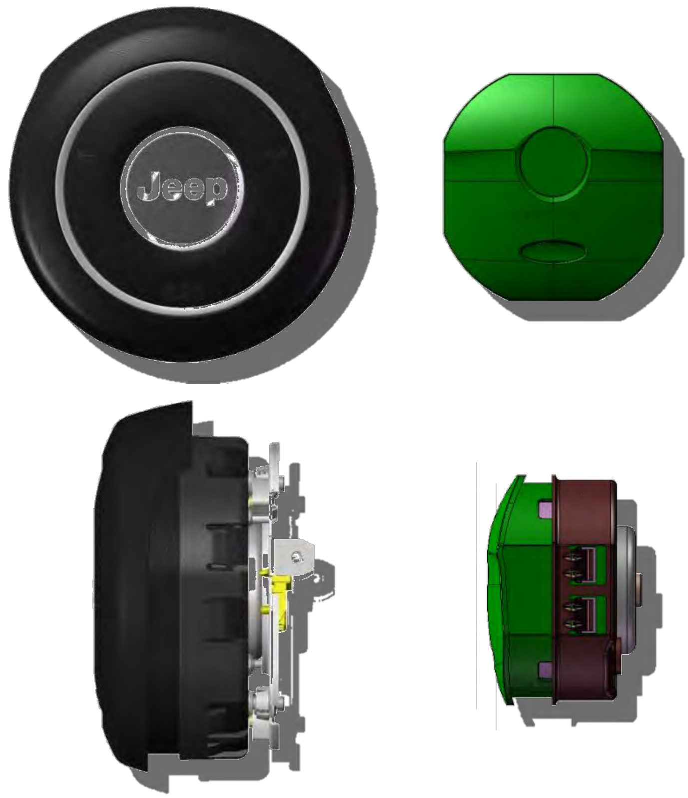



**Image 4.3-47: Standard Airbag Module (left) and VFT Module (right)**
*(Source: Courtesy of Takata)*

To keep the airbag tightly packed in a low-pressure state, it is sealed in a multi-layer plastic foil as shown in **Image 4.3-48**. This foil is the only added component in a VFT airbag module and weighs only a few grams.

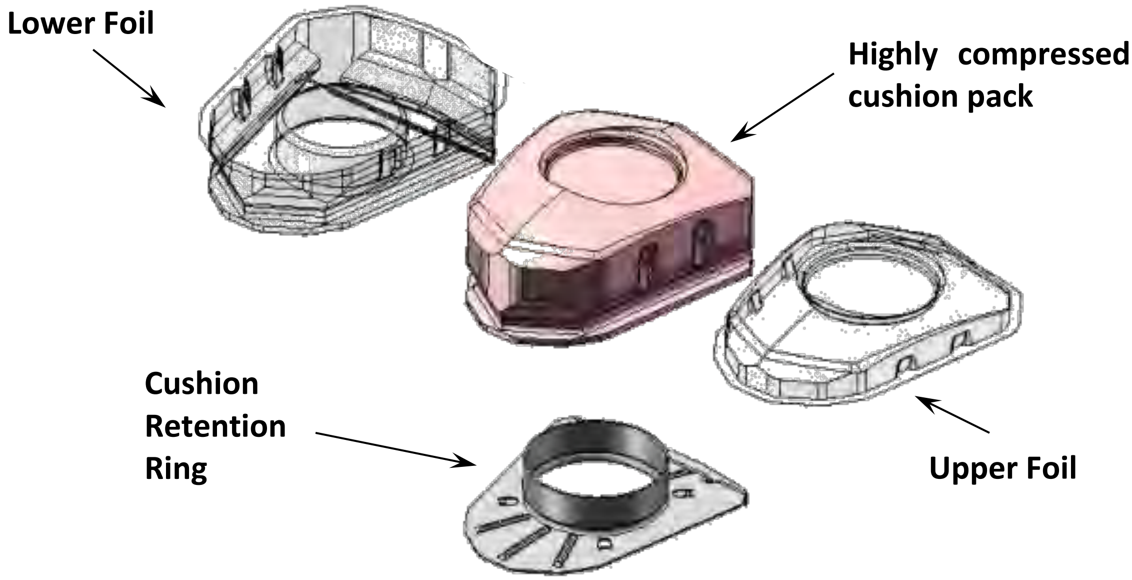



**Image 4.3-48: VFT Airbag Foil**
*(Source: Courtesy of Takata)*

The VFT airbag meets all required FMVSS and other safety standards and won a Society of Plastics Engineers award in 2010 and a Pace Award in the Process category for VFT in April of 2011. This VFT technology has already been applied to the Ferrari 458 Italia and McLaren MP4-12C (**Image 4.3-49**), which are both low-volume production vehicles. In 2012, a high-volume vehicle was released utilizing Takata's VFT airbag.

**Image 4.3-49: VFT Airbag used in Ferrari 458 Italia (left) and McLaren MP4-12C (right)**
*(Source: Courtesy of Takata)*

In addition to mass reduction, Takata's VFT airbag module also provides styling benefits allowing the steering wheel designer more freedom as the airbag module decreases in size. Smaller airbag modules may also allow for a possible standardization of hardware as surrounding components can become more common in size due to the now-predictable size of a VFT airbag.

Takata shed light upon single-stage airbag inflators, which will likely replace dual-stage inflators in the near future. Dual-stage inflators were used to vary the force and speed at which the airbag deployed based on the size and orientation of the person in the seat. This will no longer be necessary, however, as the airbags themselves are passively adapting to the passenger allowing the inflators to revert to a smaller and lighter single-stage design as shown in **Image 4.3-49**. The inflators shown are from the same vehicle generation and application for the purposes of a direct and fair comparison. The dual-stage inflator in picture (a) of **Image 4.3-50** weighs 415 grams compared to 340 grams, which is the mass of the single-stage inflator in image (b). The diameter of each inflator is the same, but the height of the single-stage is 6.8 mm less than the dual-stage.


**Image 4.3-50: Comparison of Dual- (left) and Single-Stage (right) Airbag Inflators**
*(Source: Photo Courtesy of Takata)*

Takata has also been utilizing plastic airbag housings. They have worked with DSM Engineering Plastics to use the 40% glass-filled polyamide (as shown previously for the passenger airbag housing) for steering wheel airbag housings also. A high-volume production example is shown in **Image 4.3-51**, which is currently being produced for the Chevrolet Cruze. By going to a plastic housing, assembly becomes less complicated. A plastic housing can snap to the mating plastic cover eliminating the need for fastening components thus simplifying design, reducing mass and reducing cost. **Image 4.3-52** shows a side by side comparison for the Silverado and the Cruze driver side airbags

**Image 4.3-51: Steering Wheel Airbag Housing for Chevrolet Cruze**
*(Source: Part Courtesy of Takata)*

**Image 4.3-52: Side-by-side Comparison of Chevrolet Silverado Steel Housing and the Chevrolet Cruze Plastic Airbag Housing**
*(Source: A2mac1 database)*

### 4.3.6.4 Summary of Mass Reduction Concepts Considered

Mass reduction ideas that were considered for the Occupant Restraining Device Subsystem are shown in **Table 4.3-22**. Converting the Silverado's steel airbag housing assemblies for the passenger side, driver's side knee, and steering wheel were all options as proposed by DSM. Takata's ideas noted in the previous section were also all considered along with PolyOne's Chemical Foaming Agent. Note that the estimated mass reduction percentages in **Table 4.3-24** are relative to the component(s) for that line item, not relative to the entire airbag assembly.

**Table 4.3-22: Summary of Mass Reduction Concepts Initially Considered for the Occupant Restraining Device Subsystem**

| Subsystem | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **Occupant Restraining** | | | |
| Housing, Passenger Side Airbag | Replace steel assembly with DSM's Akulon Nylon6 (40% GF) | 30-40% Mass Reduction | Remove steel housing, weight & cost |
| Ignitor, Passenger Side Airbag | Replace dual stage inflator with single stage | 10% Mass Reduction | Allows for removal of one ingniton switch |
| Housing, Steering Wheel Airbag | Replace steel assembly with DSM's Akulon Nylon6 (40% GF) | 30-40% Mass Reduction | Remove steel housing, weight & cost |
| Steering Wheel Airbag | Takata Vacuum Folding Technology (VFT) driver side airbag | 5% Mass Reduction | Smaller package size allows for smaller housing |
| Ignitor, Steering Wheel Airbag | Replace dual stage inflator with single stage | 10% Mass Reduction | Allows for removal of one ingniton switch |
| Horn Activation, Steering Wheel | Replace bracket and spring mechanism by molding into steering wheel airbag housing for a single trace horn activation system | 20-25% Mass Reduction | No stampings, no springs |
| Curtain Airbag System | Mounting brkt from steel to plastic | 15% Mass Reduction | No stampings, welding, ecoat |

### 4.3.6.5 Selection of Mass Reduction Ideas

All ideas that were considered for weight savings for this subsystem were applied as shown in **Table 4.3-23**. Each idea applied were either being used in current high-volume production or will be soon.

**Table 4.3-23: Mass Reduction Ideas Selected for Detail Analysis of the Occupant Restraining Device Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 03 | 20 | 00 | Occupant Restraining Device Subsystem | |
| 03 | 20 | 01 | **Seat Belt Assembly Front Row** | |
| 03 | 20 | 03 | **Passenger Airbag / Cover Unit** | |
| | | | Passenger Airbag Housing | Replace steel assembly with DSM's Akulon Nylon6 (40% GF) |
| 03 | 20 | 06 | **Restraint Electronics** | |
| 03 | 20 | 08 | **Seat Belts - Second Row** | |
| 03 | 20 | 12 | **Curtain Airbag System** | |
| | | | Drivers side curtain airbag mounting brkt | Replace steel with plastic PA66 |
| | | | Passenger side curtain airbag mounting brkt | Replace steel with plastic PA66 |
| 03 | 20 | 15 | **Tether Anchorages - Non Integrated** | |
| 03 | 20 | 18 | **Steering Wheel Airbag** | |
| | | | Front Cover, Steering Wheel Airbag Assy | PolyOne foaming agent |
| | | | Airbag, Steering Wheel Airbag Assy | Takata Vacuum Folding Technology (VFT) driver side airbag |
| | | | Airbag housing | Replace steel assembly with DSM's Akulon Nylon6 (40% GF) |
| | | | Ignition Canister, Steering Wheel Airbag | Replace dual stage inflator with single stage |
| | | | Horn | Replace bracket and spring mechanism by molding into steering wheel airbag housing for a single trace horn activation system |

### 4.3.6.6 Mass Reduction and Cost Impact Results

The estimated mass reduction and associated cost impacts are shown in **Table 4.3-24** for the Occupant Restraining Device Subsystem.

It should be noted that the vacuum folding technology applied to the steering wheel airbag can also be applied to other airbag modules throughout the vehicle and will likely be done so on future vehicles although it is not currently in production and was not performed in this study.

**Table 4.3-24: Mass Reduction and Cost Impact for the Occupant Restraining Device Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Net Value of Mass Reduction Idea | | | | |
| 03 | 20 | 00 | Occupant Restraining Device Subsystem | | | | | | |
| 03 | 20 | 01 | Seat Belt Assembly Front Row | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 20 | 03 | Passenger Airbag / Cover Unit | | 0.622 | $0.99 | $1.60 | 15.43% | 0.03% |
| 03 | 20 | 06 | Restraint Electronics | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 20 | 08 | Seat Belts - Second Row | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 20 | 12 | Curtain Airbag System | | 0.375 | -$0.31 | -$0.82 | 7.48% | 0.02% |
| 03 | 20 | 15 | Tether Anchorages - Non Integrated | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 20 | 18 | Steering Wheel Airbag | | 0.264 | -$3.80 | -$14.39 | 19.07% | 0.01% |
| | | | | D | 1.261 (Decrease) | -$3.12 (Increase) | -$2.47 (Increase) | 6.42% | 0.05% |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.3.7 Secondary Mass Reduction/Compounding

There were no compounding mass reductions for this system. **Table 4.3-25** summarizes the total mass and cost impact by subsystem. The systems largest savings were realized in the Seating Subsystem. Significant mass savings were also found in the Instrument Panel and Console Subsystem. Detailed system analysis resulted in 34.0 kg saved at a cost of increase $127.23, resulting in a $3.74 per kg cost increase.

**Table 4.3-25: Mass Reduction and Cost Impact for Body System Group -B-**

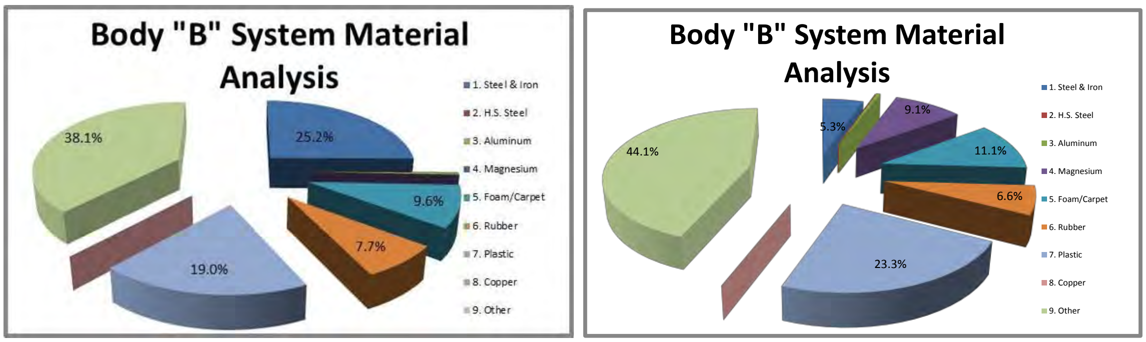
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction | | | | | | | |
| 03 | 00 | 00 | Body Group B | | | | | | | | |
| 03 | 05 | 00 | Interior Trim and Ornamentation Subsystem | 2.06 | 0.00 | 2.06 | $6.84 | $0.00 | $6.84 | $3.32 | 0.08% |
| 03 | 06 | 00 | Sound and Heat Control Subsystem (Body) | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 03 | 07 | 00 | Sealing Subsystem | 4.72 | 0.00 | 4.72 | $32.23 | $0.00 | $32.23 | $6.84 | 0.19% |
| 03 | 10 | 00 | Seating Subsystem | 19.2 | 0.00 | 19.2 | -$127.89 | $0.00 | -$127.89 | -$6.68 | 0.78% |
| 03 | 12 | 00 | Instrument Panel and Console Subsystem | 6.82 | 0.00 | 6.82 | -$35.29 | $0.00 | -$35.29 | -$5.17 | 0.28% |
| 03 | 20 | 00 | Occupant Restraining Device Subsystem | 1.26 | 0.00 | 1.26 | -$3.12 | $0.00 | -$3.12 | -$2.47 | 0.05% |
| | | | | 34.0 (Decrease) | 0.00 | 34.0 (Decrease) | -$127.23 (Increase) | $0.00 | -$127.23 (Increase) | -$3.74 (Increase) | 1.39% |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.3.8 Body Group -B- Material Analysis

A material breakdown for the base Body System -B- and for the lightweighted and compounded Engine System is provided in **Figure 4.3-5**. The “Steel & Iron” content category was reduced by nearly 20%, while “Magnesium” and “Plastic” increased by 9.1% and 4.3%, respectively.

**Baseline Body System -B-** **Total Body System -B-**




Baseline Body System -B-:

| | | Material Categories: |
|---|---|---|
| 25.2% | 62.227 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.4% | 1.111 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 9.6% | 23.694 | 5. Foam/Carpet |
| 7.7% | 18.898 | 6. Rubber |
| 19.0% | 47.010 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 38.1% | 94.077 | 9. Other |
| 100% | 247.017 | TOTAL |

Total Body System -B-:

| | | Material Categories: |
|---|---|---|
| 5.3% | 11.202 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.5% | 1.111 | 3. Aluminum |
| 9.1% | 19.282 | 4. Magnesium |
| 11.1% | 23.694 | 5. Foam/Carpet |
| 6.6% | 14.145 | 6. Rubber |
| 23.3% | 49.623 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 44.1% | 93.939 | 9. Other |
| 100% | 212.996 | TOTAL |

**Figure 4.3-5: Calculated Body System -B- Baseline Material and Total Material Content**

## 4.4 Body System -C- (Exterior)

The Body System Group -C- includes the Exterior Trim and Ornamentation, Rear View Mirror, Front End Modules and Rear End Modules Subsystems. The Front End Modules Subsystem is the largest weight contributor at 21.08 kg as shown in **Table 4.4-1**.

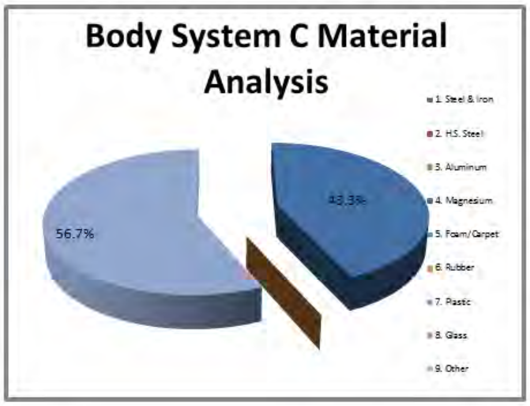
**Table 4.4-1: Baseline Subsystem Breakdown for Body System Group -C-**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 00 | 00 | Body Group C | |
| 03 | 08 | 00 | Exterior Trim and Ornamentation Subsystem | 12.824 |
| 03 | 09 | 00 | Rear View Mirrors Subsystem | 4.276 |
| 03 | 23 | 00 | Front End Modules | 21.080 |
| 03 | 24 | 00 | Rear End Modules | 2.299 |
| | | | Total System Mass = | 40.478 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 1.65% |

**Table 4.4-2: Mass Reductions and Cost Impact for System Group -C-**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys./ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | 2454 | | | | | | |
| 03 | 00 | 00 | Body Group C | | | | | | |
| 09 | 01 | 00 | Exterior Trim and Ornamentation Subsystem | | 0.989 | $1.05 | $1.06 | 7.71% | 0.04% |
| 09 | 01 | 00 | Rear View Mirrors Subsystem | | 0.373 | $0.94 | $2.51 | 8.73% | 0.02% |
| 09 | 01 | 00 | Front End Modules | | 0.575 | $0.50 | $0.87 | 2.73% | 0.02% |
| 09 | 01 | 00 | Rear End Modules | | 0.200 | $0.24 | $1.20 | 8.72% | 0.01% |
| | | | | A | 2.138 (Decrease) | $2.73 (Decrease) | $1.28 (Decrease) | 5.28% | 0.09% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase




| | | Material Categories: |
|---|---|---|
| 43.3% | 17.545 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 56.7% | 22.934 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.0% | 0.000 | 9. Other |
| 100% | 40.478 | TOTAL |

**Figure 4.4-1: Calculated Material Content For The Body System -C- Base BOM**

### 4.4.1 Exterior Trim and Ornamentation Subsystem

#### 4.4.1.1 Subsystem Content Overview

**Table 4.4-3** identifies the most significant contributor to the mass of the Exterior Trim and Ornamentation Subsystem as the radiator grill. The lower exterior finishers, upper exterior and roof finishers, rear closure finisher, emblems, cowl vent grill assembly, and subsystem attachments compose the balance of the stated mass.

**Table 4.4-3: Mass Breakdown by Sub-subsystem for Exterior Trim and Ornamentation Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 08 | 00 | Exterior Trim and Ornamentation Subsystem | |
| 03 | 08 | 01 | Radiator Grill | 6.789 |
| 03 | 08 | 02 | Lower Exterior Finishers | 2.046 |
| 03 | 08 | 04 | Upper Exterior and Roof Finish | 0.680 |
| 03 | 08 | 07 | Rear Closure Finishers | 1.157 |
| 03 | 08 | 12 | Badging | 0.310 |
| 03 | 08 | 15 | Cowl Vent Grill | 1.842 |
| | | | Total Subsystem Mass = | 12.824 |
| | | | Total System Mass = | 40.478 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 31.68% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.52% |

#### 4.4.1.2 Baseline Subsystem Technology

The Chevrolet Silverado's exterior trim and ornamentation was standard for the industry. There was a chrome-plated plastic grill with emblem, a tailgate finishing panel, and emblems. Also, there were the door finishing panels and a cowl vent screen. The materials and the thickness used are common; the differences lay in the size and the intent of their utilization.

**Image 4.4-1: Exterior Trim – Chrome-plated Plastic Grill with Emblem**


**Image 4.4-2: Exterior Trim – Tailgate Finishing Panel**

**Image 4.4-3: Exterior Trim – Door Finishing Panel**

**Image 4.4-4: Exterior Trim - Cowl Vent Grill Assembly**
*(Images 4.4-1 through 4.4-4 Source: FEV, Inc.)*

#### 4.4.1.3 Mass reduction Industry Trends

Down-gauging material thickness is the most common method used to reduce the weight of the exterior trim. Designing in reinforcements while varying material thickness for the whole component or the thickness of a specific section, can provide a significant mass reduction.

Another common industry method for mass reduction is to change materials and processes for selected components. The most promising emerging technology for hard trim is gas assist injection molding. PolyOne technology is currently used in production in industrial housings and structural foam applications as introduced in **Section 4.3**.

#### 4.4.1.4 Summary of Mass Reduction Concepts Considered

**Table 4.4-4** shows the mass reduction ideas considered for the Exterior Trim and Ornamentation Subsystem.

**Table 4.4-4: Summary of Mass Reduction Concepts Initially Considered for the Exterior Trim and Ornamentation Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Radiator Grill | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass reduction |
| Radiator Grill | Mold in Color | 0 - 10% Mass Savings | Low Cost, Little Mass Savings Potential |
| Radiator Grill | Material Change | 0 - 10% Mass Savings | Low Cost, Durability Issues |
| Lower Exterior Finishers | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass reduction |
| Lower Exterior Finishers | Mold in Color | 0 - 10% Mass Savings | Low Cost, Little Mass Savings Potential |
| Lower Exterior Finishers | Material Change | 0 - 10% Mass Savings | Low Cost, Durability Issues |
| Upper Exterior Finishers | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass reduction |
| Upper Exterior Finishers | Mold in Color | 0 - 10% Mass Savings | Low Cost, Little Mass Savings Potential |
| Upper Exterior Finishers | Material Change | 0 - 10% Mass Savings | Low Cost, Durability Issues |
| Rear Closure Finishers | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass reduction |
| Rear Closure Finishers | Mold in Color | 0 - 10% Mass Savings | Low Cost, Little Mass Savings Potential |
| Rear Closure Finishers | Material Change | 0 - 10% Mass Savings | Low Cost, Durability Issues |
| Emblems | Decals | 20% Mass Savings | Low Cost, Aesthetically Unappealing, Durabilty Issues |
| Emblems | Mold in Feature then Paint or Apply Decal | 0 - 10% Mass Savings | Low Cost, Aesthetically Unappealing |
| Cowl Vent Screen | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or No Cost Impact with Mass reduction |
| Cowl Vent Screen | Material Change | 0 - 10% Mass Savings | Low Cost, Durability Issues |

### 4.4.1.5 Selection of Mass Reduction Ideas

The mass reduction ideas selected that fell into the "A" group are shown in **Table 4.4-5**.

**Table 4.4-5: Summary of Mass Reduction Concepts Selected for the Exterior Trim and Ornamentation Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **03** | **08** | **00** | **Exterior Trim and Ornamentation Subsystem** | |
| 03 | 08 | 01 | Radiator Grill | PolyOne Process - Injection Molding |
| 03 | 08 | 02 | Lower Exterior Finishers | PolyOne Process - Injection Molding |
| 03 | 08 | 07 | Rear Closure Finishers | PolyOne Process - Injection Molding |
| 03 | 08 | 15 | Cowl Vent Screen | PolyOne Process - Injection Molding |

### 4.4.1.6 Mass Reduction and Cost Impact Estimates

The PolyOne process was utilized on the Exterior Trim and Ornamentation Sub-subsystems listed in **Table 4.4-6**. This resulted in a mass savings of 10% and a cost savings were achieved. The changes to emblems were not implemented since there were wear and durability issues with the decal life and performance.

**Table 4.4-6: Summary of Mass Reduction and Cost Impacts for the Exterior Trim and Ornamentation Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | | | | | | | |
| **03** | **08** | **00** | **Exterior Trim and Ornamentation Subsystem** | | | | | | |
| 03 | 08 | 01 | Radiator Grill | | 0.489 | $0.44 | $0.90 | 7.21% | 0.02% |
| 03 | 08 | 02 | Lower Exterior Finishers | | 0.205 | $0.26 | $1.25 | 10.00% | 0.01% |
| 03 | 08 | 04 | Upper Exterior and Roof Finish | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 08 | 07 | Rear Closure Finishers | | 0.113 | $0.12 | $1.10 | 9.76% | 0.00% |
| 03 | 08 | 12 | Badging | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 08 | 15 | Cowl Vent Grill | | 0.182 | $0.23 | $1.28 | 9.90% | 0.01% |
| | | | | | | | | | |
| | | | | A | **0.989** (Decrease) | **$1.05** (Decrease) | **$1.06** (Decrease) | **7.71%** | **0.04%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.4.2 Rear View Mirrors Subsystem

### 4.4.2.1 Subsystem Content Overview

**Table 4.4-7** shows that the most significant contributor to the mass of the Rear View Mirror Subsystem is the outside rear view mirrors. This includes both front driver and passenger side outside rear view mirrors. The inside rear view mirror and the trim cover make up the balance of the mass.

**Table 4.4-7: Mass Breakdown by Sub-subsystem for Rear View Mirrors Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 09 | 00 | Rear View Mirrors Subsystem | |
| 03 | 09 | 01 | Interior Mirror | 0.530 |
| 03 | 09 | 02 | Exterior Mirrors | 3.734 |
| 03 | 09 | 99 | Misc. | 0.012 |
| | | | Total Subsystem Mass = | 4.276 |
| | | | Total System Mass = | 40.478 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 10.56% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.17% |

**Image 4.4-5 (left): Inside Rear View Mirror**
*(Source: FEV, Inc.)*

**Image 4.4-6 (right): Outside Rear View Mirror**
*(Source: FEV, Inc.)*

### 4.4.2.2 Baseline Subsystem Technology

The Chevrolet Silverado rear view mirrors utilized materials and the thicknesses used by most automobile manufacturers and suppliers.

### 4.4.2.3 Mass Reduction Industry Trends

Down-gauging the material thickness is the most common method used to reduce mass. Designing in reinforcements while varying thickness for the whole component or the thickness of a specific section, can provide a significant mass reduction.

Another common industry method is to change materials and manufacturing processes. These component processes are altered based on materials technology and process production for interior/exterior hardware. The most promising emerging technology for hard trim is gas assist injection molding.

PolyOne technology is currently used in production in industrial housings and structural foam applications as introduced in S**ection 4.3.1**.

### 4.4.2.4 Summary of Mass Reduction Concepts Considered

**Table 4.4-8** compiles the mass reduction ideas considered for the Rear View Mirrors Subsystem.

**Table 4.4-8: Summary of Mass Reduction Concepts Initially Considered for the Rear View Mirrors Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Inside Rear View Mirror | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass Reduction |
| Outside Rear View Mirror - Left | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass Reduction |
| Outside Rear View Mirror - Right | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass Reduction |
| Trim Cover - Inside Rear View Mirror | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass Reduction |

### 4.4.2.5 Summary of Mass Reduction Concepts Selected

The mass reduction ideas selected that fell into the “A” group are shown in **Table 4.4-9**.

**Table 4.4-9: Summary of Mass Reduction Concepts Selected for the Rear View Mirrors Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **03** | **09** | **00** | **Rear View Mirrors Subsystem** | |
| 03 | 09 | 02 | Outside Rear View Mirror - Left | Gas Assist Injection Molding |
| 03 | 09 | 02 | Outside Rear View Mirror - Right | Gas Assist Injection Molding |

### 4.4.2.6 Summary of Mass Reduction Concepts and Cost Impacts

The PolyOne gas assist system was utilized for all components in **Table 4.4-10**. This resulted in a mass savings and a cost savings.

**Table 4.4-10: Summary of Mass Reduction and Cost Impact Concepts for the Rear View Mirror Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Net Value of Mass Reduction Idea | | | | |
| 03 | 09 | 00 | **Rear View Mirrors Subsystem** | | | | | | |
| 03 | 09 | 01 | Interior Mirror | | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 09 | 02 | Exterior Mirrors | | 0.373 | $0.94 | $2.51 | 10.00% | 0.02% |
| 03 | 09 | 99 | Misc. | | 0.000 | $0.94 | -- | -- | 0.00% |
| | | | | A | **0.373** (Decrease) | **$1.88** (Decrease) | **$5.03** (Decrease) | **8.73%** | **0.02%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.4.3 Front End Module Subsystem

### 4.4.3.1 Subsystem Content Overview

**Table 4.4-11** shows the total of the mass Front End Module Subsystem. The steel bumper brackets are the largest mass contributors to this subsystem, followed by the front bumper fascia (**Image 4.4-7**), the front fascia bumpers (**Image 4.4-8**) and the air dam (**Image 4.4-9**). The front bumper analysis was done along with the Body in White and resides in Body System -A-.

**Table 4.4-11: Mass Breakdown by Sub-subsystem for the Front End Module Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 23 | 00 | **Front End Modules** | |
| 03 | 23 | 02 | Module - Front Bumper and Fascia | 21.080 |
| | | | Total Subsystem Mass = | 21.080 |
| | | | Total System Mass = | 40.478 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 52.08% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.86% |

**Image 4.4-7: Front Fascia**

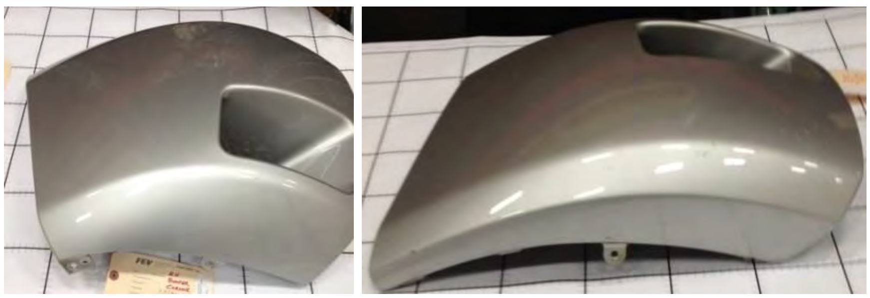


**Image 4.4-8: Front Fascia Bumpers**

**Image 4.4-9: Front Fascia Air Dam**
*(Sources: FEV, Inc.)*

#### 4.4.3.2 Baseline Subsystem Technology

The materials and thickness used are in common use by many automobile manufacturers and their suppliers.

#### 4.4.3.3 Mass Reduction Industry Trends

Down-gauging the material thickness is the most common method used to reduce mass. Designing in reinforcements while varying material thickness for the whole component or the thickness of a specific section, can provide a significant mass reduction.

Another common industry method is to change materials and manufacturing processes. These component processes are altered based on materials technology and process production for interior hardware. The most promising emerging technology for hard trim is gas assist injection molding.

MuCell technology is currently used by major OEM's like Audi, Ford, BMW and Volkswagen as introduced in **Section 4.3.** PolyOne technology is currently used in production in industrial housings and structural foam applications as introduced in **Section 4.3.1.**

### 4.4.3.4 Summary of Mass Reduction Concepts Considered

**Table 4.4-12** compiles the mass reduction ideas considered for the Front End Module Subsystem.

**Table 4.4-12: Summary of Mass Reduction Concepts Initially Considered for the Front End Module Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Front Fascia Assembly | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass reduction |
| Front Fascia Assembly | Mold in Color | 0 - 10% Mass Savings | Low Cost, Little Mass Savings Potential |
| Front Fascia Assembly | Material Change | 0 - 10% Mass Savings | Low Cost, Durability Issues |
| Air Dam | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass reduction |
| Air Dam | Mold in Color | 0 - 10% Mass Savings | Low Cost, Little Mass Savings Potential |
| Air Dam | Material Change | 0 - 10% Mass Savings | Low Cost, Durability Issues |
| Bumper Corners | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass reduction |
| Bumper Corners | Mold in Color | 0 - 10% Mass Savings | Low Cost, Little Mass Savings Potential |
| Bumper Corners | Material Change | 0 - 10% Mass Savings | Low Cost, Durability Issues |

**Summary of Mass Reduction Concepts Selected**

The mass reduction ideas selected that fell into the "$A_e$" group are shown in **Table 4.4-13**.

**Table 4.4-13: Summary of Mass Reduction Concepts Selected for the Front End Module Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **03** | **23** | **00** | **Front End Module Subsystem** | |
| 03 | 23 | 02 | Front Fascia | PolyOne Process - Injection Molding |
| 03 | 23 | 02 | Front Fascia Bumpers | PolyOne Process - Injection Molding |
| 03 | 23 | 02 | Front Fascia Air Dam | PolyOne Process - Injection Molding |

### 4.4.3.5 Mass Reduction and Cost Impact

The PolyOne gas assist system was utilized for all components in **Table 4.4-14**. This produced a mass savings and a cost savings.

**Table 4.4-14: Summary of Mass Reduction and Cost Impact for the Front End Module Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | | | | | | | |
| **03** | **23** | **00** | **Front End Modules** | | | | | | |
| 03 | 23 | 02 | Module - Front Bumper and Fascia | | 0.575 | $0.50 | $0.87 | 2.73% | 0.02% |
| | | | | | | | | | |
| | | | | **A** | **0.575** (Decrease) | **$0.50** (Decrease) | **$0.87** (Decrease) | **2.73%** | **0.02%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.4.4 Rear End Module Subsystem

### 4.4.4.1 Subsystem Content Overview

**Table 4.4-15** illustrates that the most significant contributor to the mass of the Rear End Module Subsystem is the rear bumper cover assembly. The trailer connector, spare tire release, and attachments make up the balance of the mass for this subsystem.

**Table 4.4-15: Mass Breakdown by Sub-subsystem for the Rear End Module Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 03 | 24 | 00 | Rear End Modules | |
| 03 | 24 | 02 | Module - Rear Bumper and Fascia | 2.299 |
| | | | | |
| | | | Total Subsystem Mass = | 2.299 |
| | | | Total System Mass = | 40.478 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 5.68% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.09% |

**Image 4.4-10: Rear Bumper Guard – Center**
*(Source: FEV, Inc.)*

**Image 4.4-11: Rear Bumper Guards – LH/RH Sides**
*(Source: FEV, Inc.)*

### 4.4.4.2 Baseline Subsystem Technology

The materials and thickness used are in common use by many automobile manufacturers and their suppliers.

### 4.4.4.3 Mass Reduction Industry Trends

Down-gauging the material thickness is the most common method used to reduce mass. Designing in reinforcements while varying material thickness for the whole component or the thickness of a specific section, can provide a significant mass reduction.

Another common industry method is to change materials and manufacturing processes. These component processes are altered based on materials technology and process production for interior hardware. The most promising emerging technology for hard trim is gas assist injection molding.

MuCell technology is currently used by major OEMs like Audi, Ford, BMW and Volkswagen as introduced in **Section 4.3.1**. PolyOne technology is currently used in production in industrial housings and structural foam applications as introduced in **Section 4.3.1.**

### 4.4.4.4 Summary of Mass Reduction Concepts Considered

**Table 4.4-16: Summary of Mass Reduction Concepts Initially Considered for the Rear End Module Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Rear Bumper Cover Assembly | Gas Assist Injection Molding (MuCell®, PolyOne) | 10% - 20% Mass Savings | Low or no Cost Impact with Mass reduction |
| Rear Bumper Cover Assembly | Mold in Color | 0 - 10% Mass Savings | Low Cost, Little Mass Savings Potential |
| Rear Bumper Cover Assembly | Material Change | 0 - 10% Mass Savings | Low Cost, Durability Issues |

### 4.4.4.5 Summary of Mass Reduction Concepts Selected

The mass reduction ideas selected that fell into the “A” group are shown in **Table 4.4-17.**

**Table 4.4-17: Summary of Mass Reduction Concepts Selected for the Rear End Module Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **03** | **24** | **00** | **Rear End Module Subsystem** | |
| 03 | 24 | 02 | Rear Bumper Cover Assembly | PolyOne Process - Injection Molding |

#### 4.4.4.6 Mass Reduction and Cost Impact

The PolyOne gas assist system was used for all components in **Table 4.4-19**. The result is a mass savings and a cost. All the savings is attributable to the rear bumper cover.

**Table 4.4-18: Summary of Mass-Reduction & Cost Impact Concepts Estimates for the Rear End Module Subsystem**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | | | | | | | |
| **03** | **24** | **00** | **Rear End Modules** | | | | | | |
| 03 | 24 | 02 | Module - Rear Bumper and Fascia | | 0.200 | $0.24 | $1.20 | 8.72% | 0.01% |
| | | | | | | | | | |
| | | | | A | **0.200** (Decrease) | **$0.24** (Decrease) | **$1.20** (Decrease) | **8.72%** | **0.01%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.4.5 Secondary Mass Reduction and Compounding

As seen in **Table 4.4-19**, this project recorded a system mass reduction of 2.14 kg (5.3%) at a cost decrease of $2.73, or $1.28 per kg. The contribution of the Body Group -C- system to the overall vehicle mass reduction was 0.09%. There are no compounding mass reductions for this system.

**Table 4.4-19: Summary of Mass Reduction and Cost Impact Concepts Estimates for the Body Group -C- System**

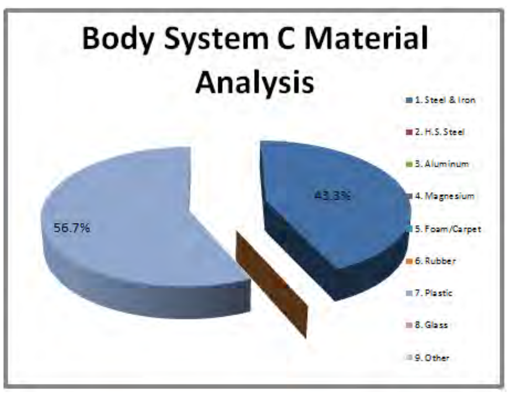
| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 03 | 00 | 00 | Body Group C | | | | | | | | |
| 09 | 01 | 00 | Exterior Trim and Ornamentation Subsystem | 0.989 | 0.00 | 0.989 | $1.05 | $0.00 | $1.05 | $1.06 | 0.04% |
| 09 | 01 | 00 | Rear View Mirrors Subsystem | 0.373 | 0.00 | 0.373 | $0.94 | $0.00 | $0.94 | $2.51 | 0.02% |
| 09 | 01 | 00 | Front End Modules | 0.575 | 0.00 | 0.575 | $0.50 | $0.00 | $0.50 | $0.87 | 0.02% |
| 09 | 01 | 00 | Rear End Modules | 0.200 | 0.00 | 0.200 | $0.24 | $0.00 | $0.24 | $1.20 | 0.01% |
| | | | | 2.14 (Decrease) | 0.00 | 2.14 (Decrease) | $2.73 (Decrease) | $0.00 | $2.73 (Decrease) | $1.28 (Decrease) | 0.09% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.4.6 Body Group -C- Material Analysis

A material breakdown for the base Body System -C- and for the lightweighted system is provided in **Figure 4.4-2.** The "Plastic" content category was reduced by 2.5%, while "Steel & Iron" increased by 2.5%.

**Baseline Body System -C-**

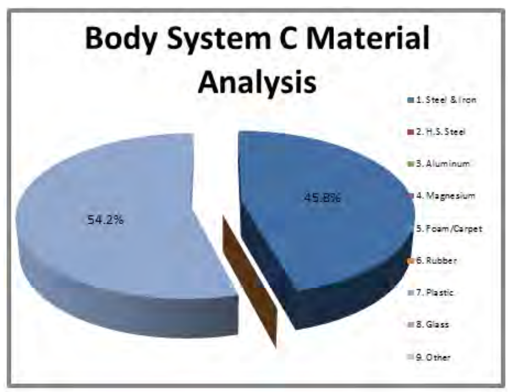



Total System Mass: 40.478 KG
89.214 LBS

Vehicle Delta: 2345.522 Kg
1.696% Portion of GVW

| | | Material Categories: |
|---|---|---|
| 43.3% | 17.545 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 56.7% | 22.934 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.0% | 0.000 | 9. Other |
| 100% | 40.478 | TOTAL |

**Total Body System -C-**




Total System Mass: 38.340 KG
84.502 LBS

Vehicle Delta: 2347.660 Kg
1.607% Portion of GVW

| | | Material Categories: |
|---|---|---|
| 45.8% | 17.545 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 54.2% | 20.795 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.0% | 0.000 | 9. Other |
| 100% | 38.340 | TOTAL |

**Figure 4.4-2: Calculated Body System -C- Baseline Material and Total Material Content**

## 4.5 Body System Group -D-

Group -D- of the Body System includes the Glazing; Handles, Locks, Latches; and Wipers and Washers Subsystems, as shown in **Table 4.5-1**. The most significant contributor to this system's mass is the Glazing Subsystem, which accounts for most of the system mass.

**Table 4.5-1: Baseline Subsystem Breakdown for the Body System Group -D-**

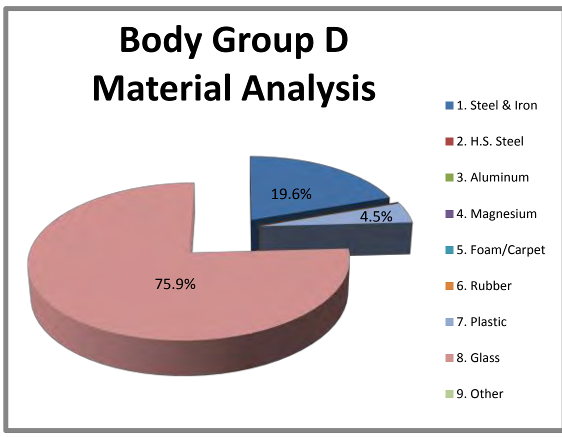
| System | Subsystem | Sub-Subsystem | Description | System/ Subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 00 | 00 | Body System (Group D) | |
| 03 | 11 | 00 | Glass (Glazing), Frame and Mechanism Subsystem | 39.597 |
| 03 | 14 | 00 | Handles, Locks, Latches and Mechanisms Subsystem | 5.659 |
| 03 | 16 | 00 | Wipers and Washers Subsystem | 5.605 |
| | | | Total Sub System Mass = | 50.861 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle Mass = | 2.07% |

As shown in **Table 4.5-2**, mass reduction ideas applied to the Glazing Subsystem resulted in the greatest weight reduction for Body System Group -D-. The Glazing Subsystem was the largest mass contributor and therefore had more opportunity to reduce weight. The overall weight savings for Body System Group -D- was 4.503 kg with a cost of $2.30. Approximately 8.85% of the Body System Group -D- mass was reduced.

**Table 4.5-2: Mass Reduction and Cost Impact for the Body System Group -D-**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Ideas: System/ Subsystem Weight "kg" | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | System/ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 03 | 00 | 00 | **Body System (Group D) Glazing** | | | | | | |
| 03 | 11 | 00 | Glass (Glazing), Frame and Mechanism Subsystem | 39.597 | 4.429 | $2.23 | $0.50 | 11.19% | 0.18% |
| 03 | 14 | 00 | Handles, Locks, Latches and Mechanisms Subsystem | 5.659 | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 16 | 00 | Wipers and Washers Subsystem | 5.605 | 0.074 | $0.06 | $0.84 | 1.32% | 0.00% |
| | | | | 50.861 (Decrease) | 4.503 (Decrease) | $2.30 (Decrease) | $0.51 (Decrease) | 8.85% | 0.18% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase




| | | Material Categories: |
|---|---|---|
| 17.9% | 9.105 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 4.2% | 2.159 | 7. Plastic |
| 77.9% | 39.597 | 8. Glass |
| 0.0% | 0.000 | 9. Other |
| 100% | 50.861 | TOTAL |

**Figure 4.5-1: Calculated Material Content for the Body System Group -D- Base BOM**

## 4.5.1 Glass (Glazing), Frame, and Mechanism Subsystem

### 4.5.1.1 Baseline Subsystem Technology

The 2011 Chevrolet Silverado passenger cabin Glazing Subsystem application is representative of the typical current industry standard. This subsystem represents all vehicle glazing (**Table 4.5-3**).

**Table 4.5-3: Baseline Subsystem for Glazing Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System/ Subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 00 | 00 | **Body System (Group D)** | |
| 03 | 11 | 00 | Glass (Glazing), Frame and Mechanism Subsystem | 39.597 |
| | | | **Total Sub System Mass =** | **39.597** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **System Mass Contribution Relative to Vehicle Mass =** | **1.61%** |

The 2011 Chevrolet Silverado has a traditional glazing system. The glass is manufactured using the age old float process developed by Pilkington in the 1950s. Traditional automotive float glass is a soda-lime glass typically consisting of sand, soda ash, dolomite, limestone, and salt cake. Colorants may be added to the mixture depending on the use.

Molten glass flows onto a tin base surface which forms a floating ribbon, perfectly flat on both sides and maintains an even thickness. As the glass flows onto the tin surface the temperature gradually drops from 1,100°C to 600°C. At 600°C the sheet of glass is removed from the tin and placed on rollers. The pressure of the opposing rollers is used to develop a uniform thickness of the glass. The glass is cut to the required size and the finishing process begins to take place.

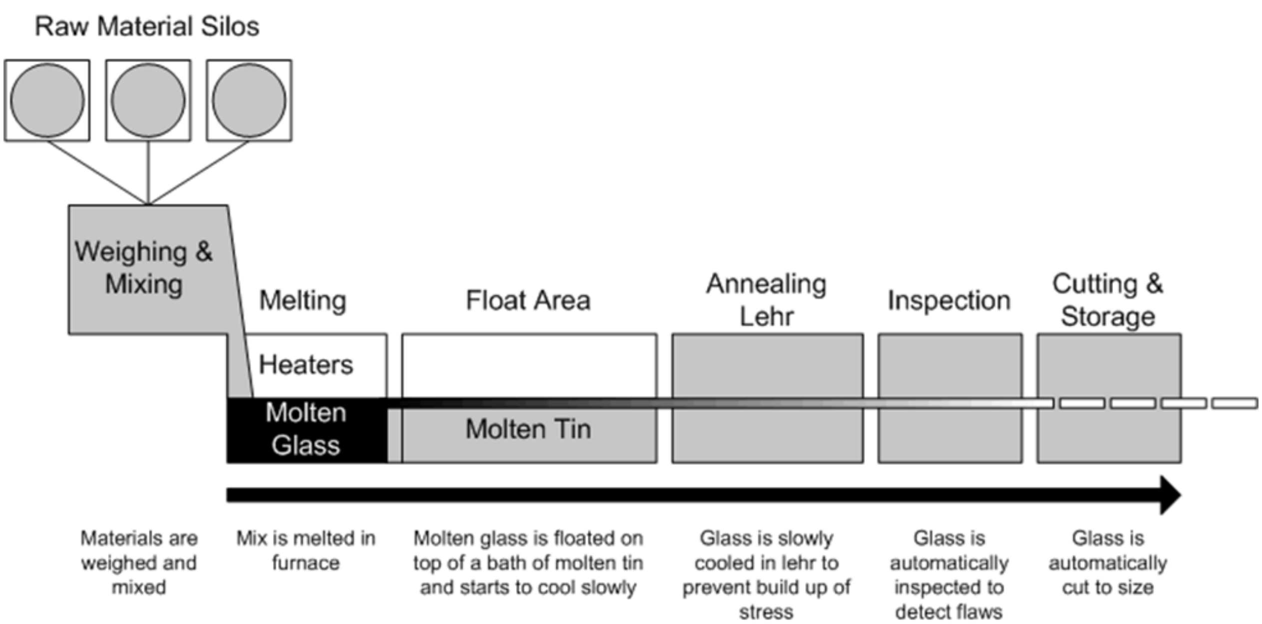



**Figure 4.5-2: Float Glass Process**
*(Source: Tangram Technology Limited - Float Glass, tangram.co.uk)*

The Glazing Subsystem has four sub-subsystems as shown in **Table 4.5-4**. The windshield is the first and is a laminated, two-panel window assembly nominally 5 mm thick. The second is the back window assembly, which is tempered glass and nominally 4 mm thick. The third and fourth sub-subsystems are the front and rear door glass. This glass is tempered as well and nominally 3.85 mm thick.

**Table 4.5-4: Glazing Subsubsystem Summary**

| System | Subsystem | Sub-Subsystem | Description | System/ Subsystem Mass "kg" |
|---|---|---|---|---|
| **03** | **11** | **00** | **Glass (Glazing), Frame, and Mechanism Subsystem** | |
| 03 | 11 | 01 | Windshield and Front Quarter Window (Fixed) | 15.865 |
| 03 | 11 | 05 | Back Window Assy | 6.588 |
| 03 | 11 | 13 | Front Side Door Glass | 8.394 |
| 03 | 11 | 14 | Rear Side Door Glass | 8.750 |
| | | | **Total Sub System Mass =** | **39.597** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **System Mass Contribution Relative to Vehicle Mass =** | **1.61%** |

### 4.5.1.2 Windshield Sub-subsystem

The Silverado windshield is a soda-lime glass sandwiched with a layer of plastic lamination between two panes of glass. The lamination is a polyvinyl butyral (PVB) sheet that provides additional impact resistant strength to the otherwise, fragile glass. The overall nominal thickness of the laminated windshield is 5.25 mm. The laminate sheet is nominally .70 mm thick, while the two panes of glass are nominally 2.27 mm each.

There are regulations which specifically pertain to the windshield safety factors of motor vehicles. These regulations and standards are developed and maintained for the purpose of reducing injuries resulting from impact with glazing surfaces. They also address the level of transparency to allow driver visibility along with the ability to block a significant amount of UV radiation. The lamination sheet also provides NVH dampening and helps insulate the passenger cabin from exterior noise.

Using laminated safety glass for the windshield helps protect occupants as the result of an accident. The lamination provides a material which allows the windshield to crack rather than shatter. It also provides some protection for passengers by impeding the possibility of their being ejected from the vehicle as the result of an accident.

#### 4.5.1.3 Rear Window Sub-subsystem

The rear window is manufactured from tempered glass and is nominally 4 mm thick. This is a single-piece assembly on the Silverado. In many cases the truck market has a sliding panel assembled into the rear window. This may require other measures in window manufacturing than was encountered on the Silverado.

**Front / Rear Side Door Windows**

The moveable side door windows are manufactured from tempered glass as well and are nominally 3.85 mm thick.

The manufacturing process of the side door and rear windows is less expensive than laminated glass. Side door and rear glass does not have the same acoustic properties of laminated glass and does not block UV rays as effectively as laminated glass.

The fragile nature of tempered glass causes it to shatter upon impact. The shattered glass crumbles into small, oval pebble shapes eliminating the danger of sharp edges.

**Tempered Safety Glass (TSG)**

Single pane tempered safety glass is the current glass of choice for all vehicle applications except the windshield. The principal advantage tempered safety glass has over laminated safety glass is reduced manufacturing costs and strength in compression and bending. The strength is less than laminated safety glass yet strong enough to withstand blunt force impact and shock. These characteristics allow TSG to provide a lower level of occupant ejection safety.

Tempered safety glass is manufactured in a very hot atmosphere with the outside layer being quickly cooled while the inner glass material is still hot. This places the glass panels in compression. This process produces a product which is tough, yet pliable, which lends itself to being formed and bent to accommodate vehicle features. The tempering process also works well for occupant safety upon glass breakage. The tempering process allows for a controlled fracture process yielding small, blocky fragments, minimizing the opportunity for these small pieces to injure occupants.

**Laminated Safety Glass (LSG)**

Laminated glass is traditionally a float process, soda-lime glass sandwiched with a layer of plastic laminate in the middle. The lamination is polyvinyl butyral (PVB) and provides additional impact resistant strength to the otherwise, fragile glass. The PVB Sheet is nominally 0.70mm thick. This assembly allows windshields to “crack” versus “shattering” when broken. The issue of shattered glass injuring the occupants was one of the driving factors in the development of laminated safety glass.

The polyvinyl butyral (PVB) layer provides additional features in reduced ultraviolet ray penetration which causes interior fabric to fade, dampening in minimizing NVH concerns, vehicle security through resistance to break in through the window, and occupant ejection protection, as a few. These features are some of the enablers for the use of laminated safety glass as replacement for tempered glass windows. The down side to this argument is laminated glass has the potential to inhibit occupant egress in an emergency situation. The argument applies to access to trapped occupants by emergency personnel as well.

There is a movement within the industry to take advantage of some of the ancillary benefits associated with LSG. Many OEM's are entertaining the use of laminated windows in place of current tempered safety glass applications, some already have. The features being highlighted are occupant safety concerns, NVH issues, and vehicle security. This trend will create an increase in mass to current applications as well as a cost increase when using current level of glazing technology.

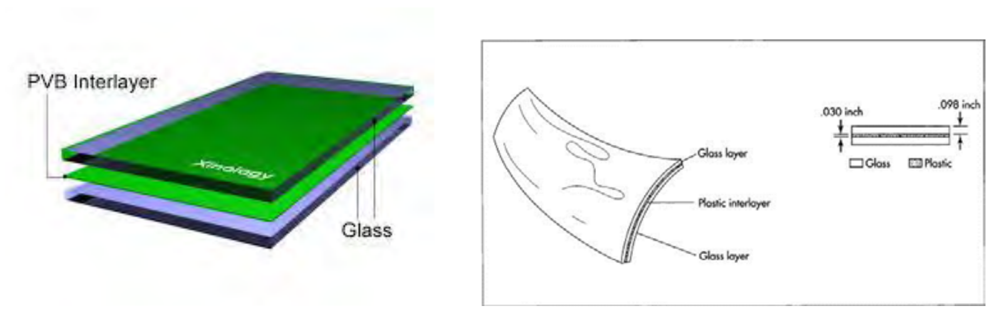



**Figure 4.5-3: Laminated Glass Assembly**
*(Sources: Left – Xinology.com, Autoclave –Free Glass Laminating Oven; Right – madehow.com, How automobile windshield is made)*

**Image 4.5-1 (Left): Laminated Glass Windshield, Broken**
*(Source: Collisionmax.com)*

**Image 4.5-2 (Right): Tempered Glass Windshield, Broken**
*(Source: faswd.com, tempered glass shatter.jpeg)*

### 4.5.1.4 Glazing Mass Reduction Industry Trends

The industry is slowly beginning a large shift in the mass reduction efforts associated with glazing applications. Many of the changes are starting to enter the market, at a slow pace. The overall cost change is yet to be understood due to the lack of maturity of the technology change. The two companies mentioned in this article are involved in the technology change and are stating a neutral cost impact once the product is mature. This claim has yet to be played out in the market place.

The industry is beginning to entertain change to the traditional soda-lime glass panel exclusive use in motor vehicle applications. All glazing applications are subject to change. The most difficult change to make will be the windshield. This is due to the occupant safety requirements, FMVSS regulations, structural stability of the vehicle, and NVH implications.

The two main suppliers are Exatec® and Sabic®, with a polycarbonate product, Lexan, to replace the storm-weathered soda-lime glass product, and Dow Corning® attempting to capture another large market with their Gorilla® Glass product technology.

The Exatec technology using polycarbonate base is a very design friendly process. This process allows a wide variety of shapes and complex contours not available in the current industry glass market. Many of these advantages are able to be color coordinated and an added benefit of the combination of multiple traditional parts into a single component.

The Corning® technology is a thinner – stronger, alkali-aluminosilicate sheet toughened glass. The Corning process is a unique forming process, mating a fusion process with innovative glass composition. This process is scalable and reliable while optimized for chemical strength and scratch and damage resistant. The Corning process produces a thin laminated glass.

**Exatec – Plasma Coated Lexan (PC)**

Exatec is a subsidiary of Sabic, making plastic components for many applications in the motor vehicle market. They already mold plastic body panels, replacing traditional metal products. They provide decorative creativity and proven over-molding technology in pursuit of entering the automobile products manufacturing battle. They already supply the automotive industry with a small variety of PC components to replace traditional glass glazing components.


**Image 4.5-3: Exatec Product Technology Examples**
*(Source: Lexan Glazing Overview 18Feb13(2).pdf, Sabic/Exatec)*

Lexan requires additional coating operations to be ready for glazing installation on motor vehicles. The base Lexan PC resin is processed through a wet coat operation during which the primer and wet coat are applied for UV protection. The second operation is an Exatec plasma coating operation creating a glass-like abrasion resistance coating.

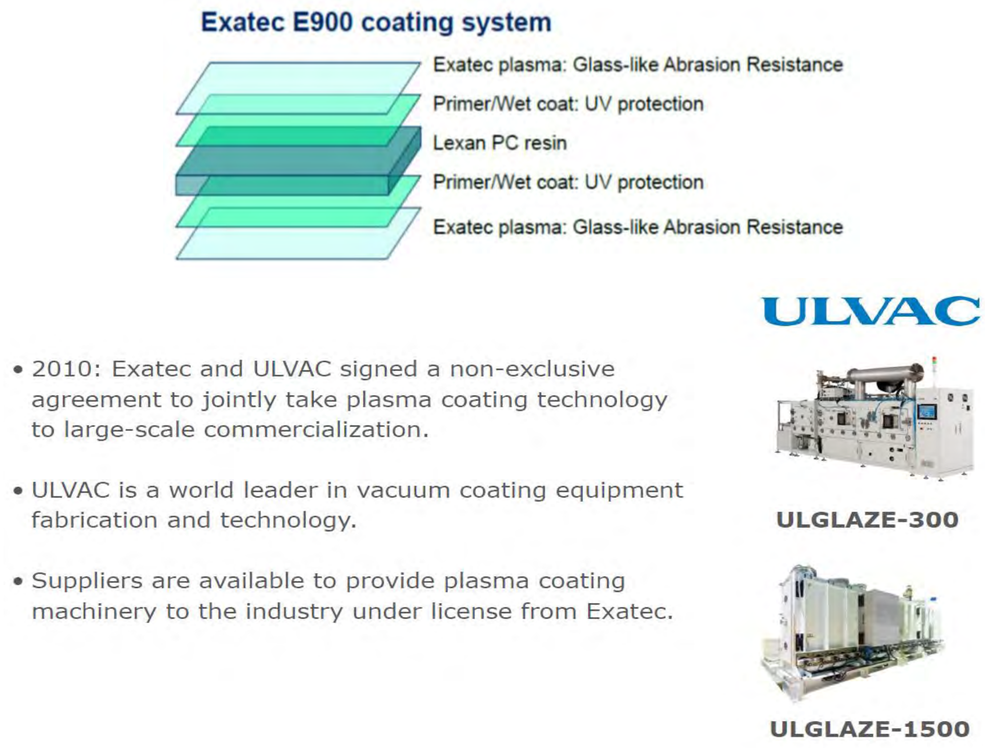



**Figure 4.5-4: Exatec Coating System**
*(Source: Lexan Glazing Overview 18Feb13(2).pdf, Sabic/Exatec)*

To further the Exatec®/Sabic® presence in the growing world market, Volkswagen introduced the Volkswagen XL1 Plug in Hybrid vehicle at the 2013 Geneva Auto Show. The Volkswagen XL1 has polycarbonate (PC) side windows with the advanced Exatec plasma coating technology from Sabic. This technology introduction is said to deliver a mass reduction of 33% over the use of conventional soda-lime glazing products.

The development of PC windshield replacement is active in Europe. This is the leading edge of future development for windshield applications. The European industry group is developing parameters and testing validation for use in the European market with focus on entry into the North American marketplace.

### Dow Corning® – Gorilla® Glass

In the 1960s, Dow Corning developed a tough, but light glass known as Chemcor®, which eventually was used for tableware, ophthalmic products, and eventually applications for automotive, aviation, and the pharmaceutical industry.

In the early 2000s and the introduction of the first iPhones, Apple CEO Steve Jobs met with Corning CEO Weldon Weeks and explained he wanted the product's screen made of glass. Corning® began development of a tough cover glass for electronic devices in 2006. The iPhone was unveiled in January 2007 and went on sale in late the following June.

Future development of Gorilla Glass for advanced electronic devices led Corning to evaluate automotive industry applications.

Gorilla Glass is an alkali-aluminosilicate sheet toughened glass. Dow Corning states the material's primary properties are strength (allowing thin glass without fragility), high scratch resistance (protective coating), hardness (with the Vickers hardness test rating of 622 – 701), and that the material can be recycled. The strength of Gorilla Glass is in the processing of the thin sheet. With the material change the compression layer is stronger and is pushed deeper into the sheet of glass. The depth allows small surface flaws and imperfections to be present yet not propagate beyond the compression layer boundary (**Figure 4.5-5**).

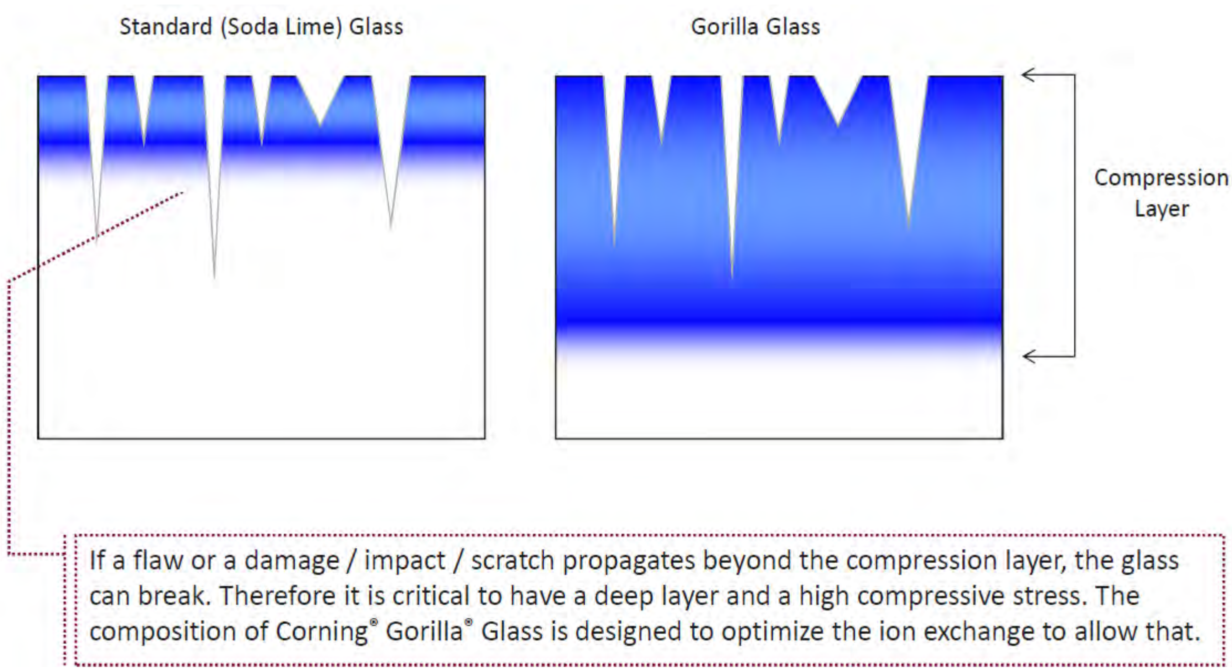



**Figure 4.5-5: Gorilla Glass Automotive Glazing**
*(Source: Corning Gorilla Glass for Automotive Glazing, Corning Incorporated, 5th Environmentally-Friendly Vehicle Conference, Baltimore, MD, 12 Sep 2012, Slide #4)*

Corning Gorilla Glass was a late addition to the mass reduction mix. **Table 4.5-5** demonstrates the mass reduction opportunity provided by the Corning product line.

Corning is not currently in the production mode for Gorilla Glass for the automotive industry. They continue to develop this product and expect to be ready to enter the automotive markets with Gorilla Glass within the next 10 years.

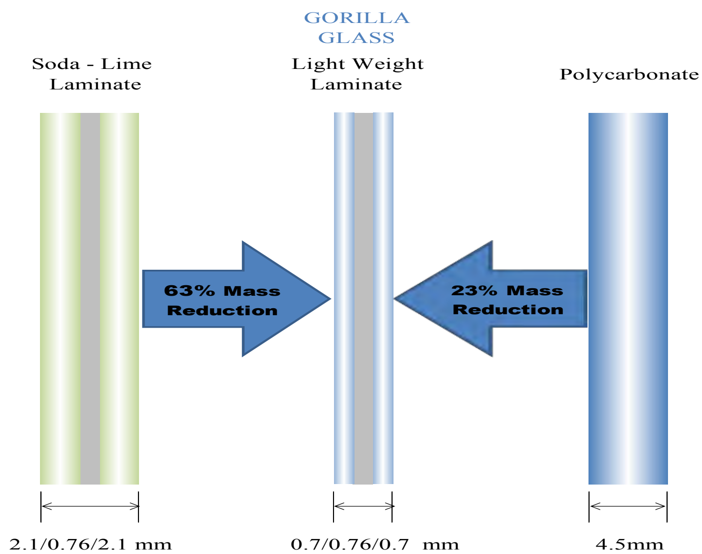



**Figure 4.5-6: Overall Mass Reduction Summary**
*(Source: Corning Gorilla Glass for Automotive Glazing, Corning Incorporated, 5th Environmentally-Friendly Vehicle Conference, Baltimore, MD, 12 Sep 2012, Slide #7)*

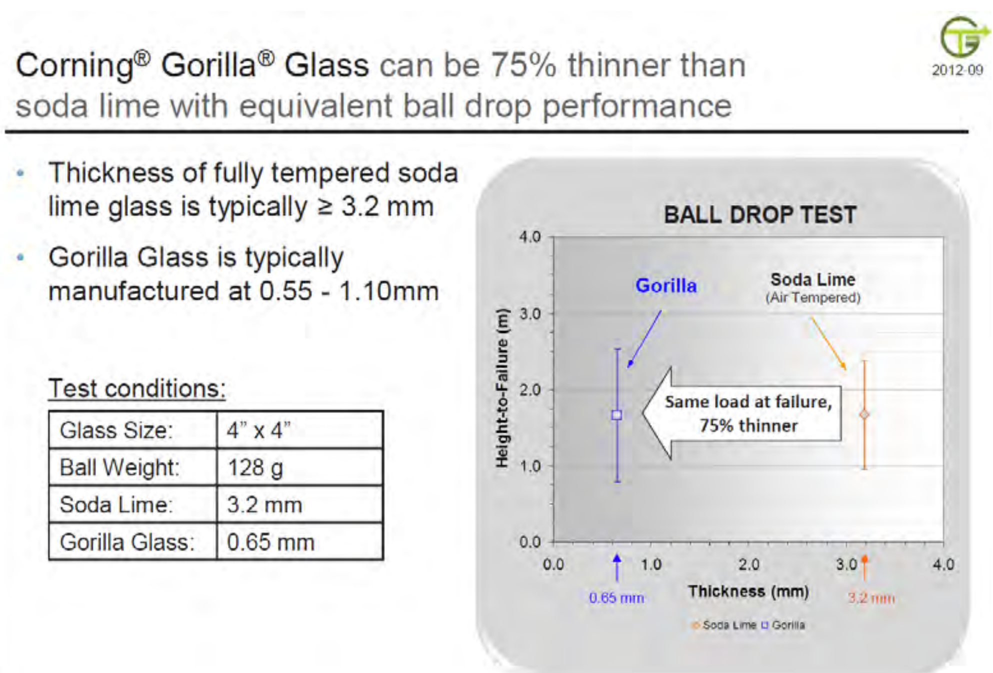



**Figure 4.5-7: Gorilla® Glass Ball Drop Test Results**
*(Source: Corning Gorilla Glass for Automotive Glazing, Corning Incorporated, 5th Environmentally-Friendly Vehicle Conference, Baltimore, MD, 12 Sep 2012, Slide #5)*

**Table 4.5-5: Gorilla® Glass Mass Reduction Opportunity (Laminated)**

| Component / Assembly | Total Glass Area $m^2$ | Mass Reduction Opportunity (Lamination not included) | | Potential Savings | | |
|---|---|---|---|---|---|---|
| | | Glass Material | Glass Thickness | Base Mass (Kg.) | Mass Reduction (Kg.) | Reduction Percentage |
| Windshield | 1.32 | Soda Lime:<br>Gorilla Glass: | 2.1mm x 2.1mm<br>0.7mm x 0.7mm | 14.9<br>5.6 | 9.3 | 62.42% |
| Sunroof | 1.00 | Soda Lime:<br>Gorilla Glass: | 4.85mm<br>0.7mm x 0.7mm | 12.1<br>4.2 | 7.9 | 65.29% |
| Side Lites | 1.67 | Soda Lime:<br>Gorilla Glass: | 3.85mm<br>0.7mm x 0.7mm | 20.3<br>7.1 | 13.2 | 65.02% |
| Back Lites | 0.96 | Soda Lime:<br>Gorilla Glass: | 3.85mm<br>0.7mm x 0.7mm | 11.6<br>4.1 | 7.5 | 64.66% |

*(Source: Corning Gorilla Glass for Automotive Glazing, Corning Incorporated, 5th Environmentally-Friendly Vehicle Conference, Baltimore, MD, 12 Sep 2012, Slide #8)*

Gorilla® glass is a laminated product and all glazing applications for this product are thus laminated instead of tempered. This change may require NHTSA approval for egress, although some manufacturers are starting to use laminated glass to minimize NVH concerns. It provides the same benefits as any other laminated glass: It does not shatter like tempered glass, which provides some enhanced crash protection in reducing ejections. It provides NVH improvements and better theft protection against smashed glass to gain entry.

**Table 4.5-6: Glazing Technology Mass Reduction Opportunity**

Glazing Technology Mass - Reduction Opportunity

| Base Component / Assembly | Total Glass Area $m^2$ | Qty. | | Mass Reduction Opportunity | | Potential Savings Soda Lime Glass | | | Potential Savings Exatec® PC | | | Potential Savings | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Glass Material | Glass Thickness | Base Mass (Kg.) | Mass Reduction (Kg.) | Reduction Percentage | Base Mass (Kg.) | Mass Reduction (Kg.) | Reduction Percentage | Base Mass (Kg.) | Mass Reduction (Kg.) | Reduction Percentage |
| Windshield | 1.32 | 1 | Base | Soda Lime: | 2.1mm x 2.1mm | 14.9 | 1.49 | 10.00% | | | | 14.9 | | |
| | | 1 | Exatec® | Lexan (PC): | 4.5mmx 4.5mm | | | | Not currently under developed in the USA | | | | | |
| | | 1 | Corning® | Gorilla Glass: | 0.7mm x 0.7mm | | | | | | | | 9.387 | 63.00% |
| Side Door Windows | 1.67 | 2 | Base | Soda Lime: | 3.85mm | 40.6 | 10.15 | 25.00% | 81.2 | | | 81.2 | | |
| | | 4 | Exatec® | Lexan (PC): | 4.5mmx 4.5mm | | | | | 26.80 | 33.00% | | | |
| | | 4 | Corning® | Gorilla Glass: | 0.7mm x 0.7mm | | | | | | | | 51.156 | 63.00% |
| Rear Windows | 0.96 | 1 | Base | Soda Lime: | 3.85mm | 11.6 | 1.972 | 17.00% | 11.6 | | | 11.6 | | |
| | | 1 | Exatec® | Lexan (PC): | 4.5mmx 4.5mm | | | | | 3.83 | 33.00% | | | |
| | | 1 | Corning® | Gorilla Glass: | 0.7mm x 0.7mm | | | | | | | | 7.308 | 63.00% |
| Subsystem Mass-Reduction Opportunities per Technology | | | | | | 67.1 | 13.61 | 20.29% | 92.8 | 30.62 | 33.00% | 107.7 | 67.85 | 63.00% |
| | | | | | | Soda Lime (Base) | | | Exatec® PC | | | Corning® Gorilla® Glass | | |

**Base Information to compare the various technologies used was a part of a Corning® Gorilla® Glass presentation for the 5th Environmentally -Friendly Vehicles Conference, Baltimore, MD, 12 Sep 2012.

*(Source: FEV, Inc.)*

**Table 4.5-7** presents the mass reduction ideas that were considered for implementation on the Chevrolet Silverado Glazing Sub-subsystem. Changes to the current glazing industry technology were more strongly considered due to the lack of maturity of the Exatec/Sabic and Corning Gorilla Glass product lines.

**Table 4.5-7: Summary of Mass Reduction Concepts Initially Considered for Glazing Subsystem**

| Component / Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade Offs and / or Benefits |
|---|---|---|---|
| Windshield | Reduce Inner glass layer thickness from 2.27mm to 1.6mm | 10% Mass-Reduction | Minimal cost increase. Possible NVH and cabin noise increase. |
| Rear Window | Reduce thickness from 4.00mm to 3.15mm | 17% Mass-Reduction | Minimal cost increase. Currently installed in Dodge Durango. |
| Rear Window | Replace with PolyCarbonate Glazing | 33% Mass-Reduction | Minimal risk. Sabic/Exatec introduced at 2013 Geneva Auto Show on VW XL1. Greater design flexibility. |
| Rear Window | Replace Tempered Glass with Laminated Gorilla® Glass | 25% Mass-Reduction | Possible passenger safety concern with egress. Incremental cost increased. |
| Front and Rear Side Door Windows | Replace Tempered Glass with Laminated Gorilla® Glass | 25% Mass-Reduction | Possible passenger safety concern with egress. Incremental cost increased. |
| Front and Rear Side Door Windows | Replace with PolyCarbonate Glazing | 33% Mass-Reduction | Minimal risk. Sabic/Exatec introduced at 2013 Geneva Auto Show on VW XL1. Greater design flexibility. |
| Front and Rear Side Door Windows | Reduce thickness from 3.85mm to 3.15mm. | 20% Mass-Reduction | Minimal cost increase. Possible NVH and cabin noise increase. 3.15mm thickness is standard in EU. |

The advantage in the implementation of mass reduction ideas may change the focus of these two companies, as well as others, once mass reduction efforts become more mainstream activity. There is enough flexible creativity in the base products offered by these companies to allow them to continue development efforts to introduce new technology on a wide basis in the not too distant future. The unknown business cost model may become a deterrent and drag development on for a longer period of time.

Both technologies provide valuable steps forward in the mass reduction effort. They are also diverse enough to not be stepping on each other’s toes. Both technologies provide advantages which should allow them to mature, and become viable players in the automotive glazing industry. There are advantages to the vehicle OEM’s and to the energy conscious consumer which can be leveraged for the good of mankind.

None of the new technology ideas were chosen due to the lack of product maturity and the optimistic cost model projections. Their efforts will continue and their products will slowly come to market over the next few years as the mass reduction effort flourishes.

### 4.5.1.5 Selection of Mass Reduction Ideas

**Table 4.5-8** presents the selected mass reduction ideas for Glazing Subsystem of the Chevrolet Silverado. Glass panel thickness reduction was the choice of the day. These were the only activities which can be implemented with confidence in success. With the

Volkswagen breakthrough at the Geneva Auto Show in 2013, there breathes some hope into mass production of lighter mass, replacement components for the current glazing applications in motor vehicles.

As you review the support material for this report you will see there are significant opportunities to reduce mass in the Glazing Subsystem. The lack of product test data has to limit our enthusiasm in stating they will be able to be implemented within the timetable covered by this report.

If all of the projections provided by Exatec/Sabic and Corning Gorilla Glass product support activities become reality, there is a potential to reduce the Glazing Subsystem mass by someplace between 23% and 63% mass reduction at no cost.

**Table 4.5-8: Mass Reduction Ideas Selected for Glazing Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Subsubsystem Description | Mass- Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| 03 | 11 | 00 | Glass (Glazing), Frame and Mechanism Subsystem | |
| 03 | 11 | 01 | Windshield | Reduce Windshield Inner Glass Panel thickness from 2.27mm to 1.6mm |
| 03 | 11 | 05 | Back Window (Fixed) | Reduce Rear Window Glass Panel thickness from 4.00mm to 3.15mm |
| 03 | 11 | 13 | Rear Side Door Glass | Reduce Rear Door Glass Panel thickness from 3.85mm to 31.5mm |

#### 4.5.1.6 Mass Reduction and Cost Impact Results

**Table 4.5-9** presents the selected mass reduction ideas which were chosen, the mass reduction associated with each mass reduction idea, along with the cost impact.

Mass reduction ideas applied to the windshield, rear window assembly, and rear side door windows are accomplished through the thinning of the glass layer. The thickness of the inner laminated glass panel of the windshield was reduced from 2.27mm to 1.6mm. This change results in a mass reduction of 1.59 kg at a cost save of $0.80.

Thinning was applied to the TSG rear window reducing the thickness form 4.00mm to 3.15mm, resulting in a mass reduction of 1.343 kg and a cost save of $0.68

The rear door windows were also thinned from 3.85 mm to 3.15 mm. This reduction is supported by the fact the 3.15 mm door window thickness is the EU standard. This may result in some adverse NVH concerns in this class of vehicle but feel confident this will not be the case. The thinning process, from 3.85 mm to 3.15 mm, yielded a mass reduction of 1.496 kg at a cost save of $0.76.

The front door window was not a mass reduction consideration due to adverse NVH concerns related to thinning these glass panels.

**Table 4.5-9: Sub-Subsystem Mass Reduction and Cost Impact for the Glazing Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Ideas | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | System/ Subsystem Weight "kg" | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | System/ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 03 | 11 | 00 | **Glass (Glazing), Frame, and Mechanism Subsystem** | | | | | | |
| 03 | 11 | 01 | Windshield and Front Quarter Window (Fixed) | 15.865 | 1.590 | $0.80 | $0.50 | 10.02% | 0.06% |
| 03 | 11 | 05 | Back Window Assy | 6.588 | 1.343 | $0.68 | $0.50 | 20.39% | 0.05% |
| 03 | 11 | 13 | Front Side Door Glass | 8.394 | 0.000 | $0.00 | $0.00 | -- | 0.00% |
| 03 | 11 | 14 | Rear Side Door Glass | 8.750 | 1.496 | $0.76 | $0.51 | 17.10% | 0.06% |
| | | | | 39.597 (Decrease) | 4.429 (Decrease) | $2.23 (Decrease) | $0.50 (Decrease) | 11.19% | 0.18% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.5.2 Handles, Locks, Latches and Mechanisms Subsystem.

### 4.5.2.1 Subsystem Overview

**Table 4.5-10** shows the mass breakdown of the Handles, Locks, Latches and Mechanisms Subsystem.

**Table 4.5-10: Mass Breakdown Subsystem for Handles, Locks, Latches and Mechanisms Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System/ Subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 00 | 00 | **Body System (Group D)** | |
| 03 | 14 | 00 | Handles, Locks, Latches and Mechanisms Subsystem | 5.659 |
| | | | Total Sub System Mass = | 5.662 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle Mass = | 0.23% |

Due to program restraints and low yield of mass reductions on the subsystem it was determined that this subsystem would not be estimated.

### 4.5.3 Wipers and Washers Subsystem

#### 4.5.3.1 Subsystem Content Overview

**Table 4.5-11** shows the mass breakdown of the Wipers and Washers Subsystem.

**Table 4.5-11: Mass Breakdown for Wipers and Washers Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | System/ Subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 00 | 00 | **Body System (Group D)** | |
| 03 | 16 | 00 | Wipers and Washers Subsystem | 5.605 |
| | | | **Total Sub System Mass =** | **5.605** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **System Mass Contribution Relative to Vehicle Mass =** | **0.23%** |

As shown in **Table 4.5-12**, the Wiper Assembly Front and Miscellaneous Sub-subsystems are included in the Wipers and Washers Subsystem.

**Table 4.5-12: Mass Breakdown by Sub-subsystem for Wipers and Washers Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System/ Subsystem Mass "kg" |
|---|---|---|---|---|
| 03 | 16 | 00 | **Wipers and Washers Subsystem** | |
| 03 | 16 | 01 | Wiper Assembly Front | 4.631 |
| 03 | 16 | 99 | Misc. | 0.975 |
| | | | **Total Sub System Mass =** | **5.605** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **System Mass Contribution Relative to Vehicle Mass =** | **0.23%** |

#### 4.5.3.2 Baseline Subsystem Technology

The wipers combine two mechanical systems to perform their task: an electric motor and worm gear reduction provides power to the wipers. A linkage converts the rotational output of the motor into the back-and-forth motion of the wipers. The worm gear reduction can multiply the torque of the motor by 40 times, while slowing the output speed of the electric motor by 40 times as well. The output of the gear reduction operates the linkage that moves the wipers back and forth. A lever arm is attached to the output shaft of the gear reduction; the lever arm rotates as the wiper motor turns. The lever is connected to a rod and the rotational motion of the lever moves the rod back and forth. The longer rod is connected to a shorter rod that actuates the wiper blade on the driver side. Another linkage transmits the force from the driver-side to the passenger-side wiper blade.

**Image 4.5-4: Wiper Assembly**
*(Source: FEV, Inc.)*

**Image 4.5-5: Solvent Bottle**
*(Source: FEV, Inc.)*

#### 4.5.3.3 Mass Reduction Industry Trends

Some of the different wiper blade schemes used by various automotive manufacturers include:

<u>Pivot Points</u> **–** Many vehicles have similar wiper designs: Two blades which move together to clean the windshield. One of the blades pivots from a point close to the driver's side of the car, and the other blade pivots from near the middle of the windshield. This is the "Tandem System." This design clears most of the windshield that is in the driver's field of view.

There are other designs used on automobiles. Mercedes uses a single wiper arm that extends and retracts as it sweeps across the window – Single Arm (Controlled). This design also provides good coverage, but is more complicated than the standard dual-wiper systems. Some systems use wiper blades mounted on opposite sides of the windshield and move in opposing directions. Other vehicles have a single wiper mounted in the middle.

<u>Blades</u> **–** The beam (flat) blade wiper blade (**Image 4.5-6**) is the main trend in wiper blade design. The market drivers are product quality and durability. The contact pressure over the wiper blade element is no longer distributed by the claws of the wiper bracket, but by a spring specifically designed to optimize wiper blade contact with the windshield.


**Image 4.5-6 (Left): Beam (Flat) Blade**

**Image 4.5-7 (Right): Conventional Blade**

*(Source: FEV, Inc.)*

<u>Drive Units</u> **–** Another trend is the fact that many wiper systems are being controlled by electronic drive units which determine the arc of wipe and speed. There are few wiper systems that solely move the wiper blades back and forth without electronic speed control, except on some entry level vehicles.

Direct drive systems for windshield wipers are currently in production by Bosch and Valeo for a number of recently launched carlines. The two drives of a dual motor wiper system do not require an additional mechanical linkage and are therefore smaller than traditional wiper systems. The mass of each unit is approximately half a liter. The new Bosch direct drive system needs up to 75% less space and is over a kilogram lighter than standard drive and linkage systems. Each wiper has its own compact drive motor and is mounted directly on the drive shaft, which makes the new system easier to integrate into vehicles. Since the direct drives require no linkage, there is more room for other components in the engine compartment. An electronic control unit takes the place of the mechanical linkage. The control unit synchronizes the two drives by monitoring the position of the two wiper arms. Each drive unit consists of a mechatronic drive that can run either backwards or forwards. Specifications for the sweep angle and rest position are programmable. This allows the wiper systems to be designed symmetrically for right and left hand drive since the blade alignment is controlled by the software.

### 4.5.3.4 Summary of Mass Reduction Concepts Considered

**Table 4.5-13** compiles the mass reduction ideas considered for the Wiper and Washers Subsystem.

**Table 4.5-13: Summary of Mass Reduction Concepts Initially Considered for the Wipers and Washers Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **Wipers and Washers Subsystem** | | | |
| Solvent bottle | PolyOne® | 10% Mass Reduction | Cost reduction dur to faster cycle times and lower press tonnage |
| Solvent bottle | Mucell® | 10% Mass Reduction | Bottle may seep due to gas bubble openings |
| Solvent bottle | 3m Glass bubblesI® | 8% Mass Reduction | High cost of material and has to be pre-mixed |

**Selection of Mass Reduction Ideas**

The mass reduction ideas selected for detailed analysis are shown in **Table 4.5-14.**

**Table 4.5-14: Summary of Mass Reduction Concepts Selected for the Wipers and Washers Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| 03 | 16 | 00 | **Wipers and Washers Subsystem** | |
| 03 | 16 | 99 | **Misc.** | |
| | | | Solvent bottle | PolyOne® foaming agent |

### 4.5.3.5 Mass Reduction and Cost Impact

**Table 4.5-15: Summary of Mass Reduction and Cost Impact for the Wipers and Washers Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Ideas: System/ Subsystem Weight "kg" | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | System/ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 03 | 16 | 00 | **Wipers and Washers Subsystem** | | | | | | |
| 03 | 16 | 01 | Wiper Assembly Front | 4.631 | 0.000 | $0.00 | -- | -- | 0.00% |
| 03 | 16 | 99 | Misc. | 0.975 | 0.074 | $0.06 | $0.84 | 7.61% | 0.00% |
| | | | | 5.605 (Decrease) | 0.074 (Decrease) | $0.06 (Decrease) | $0.84 (Decrease) | 1.32% | 0.00% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.5.4 Secondary Mass Reduction and Compounding

As seen in **Table 4.5-16**, this project recorded a system mass reduction of 4.50 kg (8.85%) at a cost decrease of $2.30, or $0.51 per kg. The contribution of the Body Group -D- system to the overall vehicle mass reduction was 0.19%. There are no compounding mass reductions for this system.

**Table 4.5-16: Mass Reduction and Cost Impact for the Body System Group -D-**

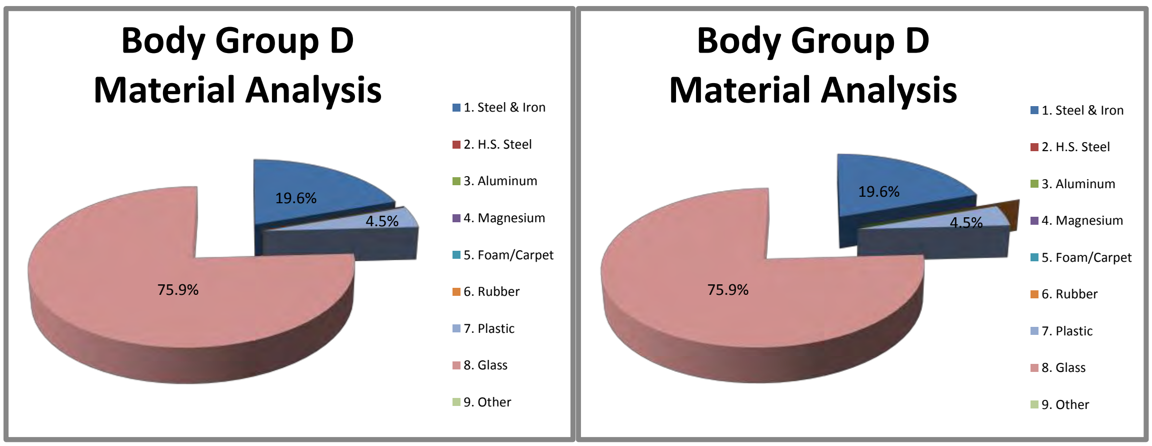
| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 03 | 00 | 00 | **Body System (Group D) Glazing** | | | | | | | | |
| 03 | 11 | 00 | Glass (Glazing), Frame and Mechanism Subsystem | 4.429 | 0.00 | 4.43 | $2.23 | $0.00 | $2.23 | $0.50 | 0.18% |
| 03 | 14 | 00 | Handles, Locks, Latches and Mechanisms Subsystem | 0.000 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 03 | 16 | 00 | Wipers and Washers Subsystem | 0.074 | 0.00 | 0.07 | $0.06 | $0.00 | $0.06 | $0.84 | 0.00% |
| | | | | 4.50 (Decrease) | 0.00 | 4.50 (Decrease) | $2.30 (Decrease) | $0.00 | $2.30 (Decrease) | $0.51 (Decrease) | 0.18% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.5.5 Body Group -D- Material Analysis

A material breakdown for the base Body System -D- and for the lightweighted system is provided in **Figure 4.5-8**. The “Glass” content category was reduced by 2.0%, while “Steel & Iron” increased by 1.7%.

**Baseline Body System -D-** **Total Body System -D-**




| | | Material Categories: |
|---|---|---|
| 17.9% | 9.105 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 4.2% | 2.159 | 7. Plastic |
| 77.9% | 39.597 | 8. Glass |
| 0.0% | 0.000 | 9. Other |
| 100% | 50.861 | TOTAL |

| | | Material Categories: |
|---|---|---|
| 19.6% | 9.105 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 4.5% | 2.085 | 7. Plastic |
| 75.9% | 35.168 | 8. Glass |
| 0.0% | 0.000 | 9. Other |
| 100% | 46.358 | TOTAL |

**Figure 4.5-8: Calculated Body System -D- Baseline Material and Total Material Content**

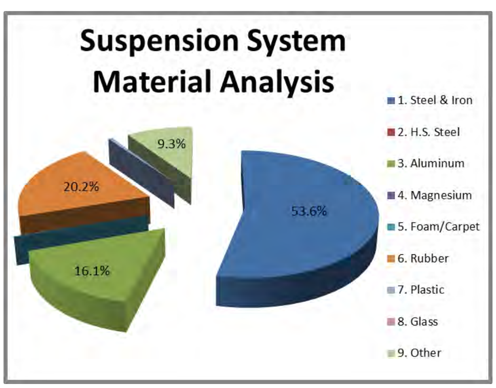
## 4.6 Suspension System

The Suspension System is composed of four subsystems: the front suspension, rear suspension, shock absorber, and wheels and tires (**Table 4.6-1**). The greatest mass is in the Wheels and Tires Subsystem with approximately 52.7% of the total system mass.

**Table 4.6-1: Baseline Subsystem Breakdown for the Suspension System**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 04 | 00 | 00 | **Suspension System** | |
| 04 | 01 | 00 | Front Suspension Subsystem | 54.8 |
| 04 | 02 | 00 | Rear Suspension Subsystem | 63.5 |
| 04 | 03 | 00 | Shock Absorber Subsystem | 24.4 |
| 04 | 04 | 00 | Wheels And Tires Subsystem | 158.6 |
| | | | | |
| | | | **Total System Mass =** | **301.2** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **System Mass Contribution Relative to Vehicle =** | **12.3%** |

The Material Categories for the Baseline Suspension System are shown in **Figure 4.6-1.** "Steel & Iron" is the leading category, with 53.6% (161.5 kg) of the overall mass, followed by rubber at 20.2% (61.0 kg), and aluminum at 16.1% (48.5 kg). The "Other" category includes assemblies that have multiple materials, such as ball joints and stabilizer links.




| | | Material Categories: |
|---|---|---|
| 53.6% | 161.5 | 1. Steel & Iron |
| | 0.0 | 2. H.S. Steel |
| 16.1% | 48.5 | 3. Aluminum |
| | 0.0 | 4. Magnesium |
| 0.14% | 0.42 | 5. Foam/Carpet |
| 20.2% | 61.0 | 6. Rubber |
| 0.57% | 1.73 | 7. Plastic |
| | 0.0 | 8. Glass |
| 9.34% | 28.1 | 9. Other |
| 100% | 301.2 | TOTAL |

**Figure 4.6-1: Baseline Suspension System Material Distribution**

**Table 4.6-2** summarizes the total mass and cost impact by subsystem. The systems largest savings were realized in the Rear Suspension Subsystem. Significant mass savings were also found in the Wheels And Tires, and Front Suspension Subsystems. Detailed system analysis with compounding resulted in 105.4 kg saved at a cost of $157.76, resulting in a $1.50 per kg cost increase.

**Table 4.6-2: Mass Reduction and Cost Impact for Suspension System**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | System/ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 04 | 00 | 00 | Suspension System | | | | | | |
| 04 | 01 | 00 | Front Suspension Subsystem | C | 21.3 | -$23.71 | -$1.11 | 7.08% | 0.87% |
| 04 | 02 | 00 | Rear Suspension Subsystem | D | 35.7 | -$113.47 | -$3.17 | 11.87% | 1.46% |
| 04 | 03 | 00 | Shock Absorber Subsystem | B | 6.44 | -$3.77 | -$0.58 | 2.14% | 0.26% |
| 04 | 04 | 00 | Wheels And Tires Subsystem | X | 19.6 | -$119.89 | -$6.13 | 6.49% | 0.80% |
| | | | | | | | | | |
| | | | | D | 83.1 (Decrease) | -$260.84 (Increase) | -$3.14 (Increase) | 27.6% | 3.39% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.6.1 Front Suspension Subsystem

### 4.6.1.1 Subsystem Content Overview

**Image 4.6-1** shows the major suspension components in the Front Suspension Subsystem.

**Image 4.6-1: Front Suspension Subsystem**
*(Source: A2MAC1)*

As seen in **Image 4.6-2**, the Front Suspension Subsystem consists of the major components of the upper and lower control arms, front knuckle assemblies, front stabilizer bar, bushings and mounts, and the miscellaneous attaching components.

**Image 4.6-2: Front Suspension Subsystem Current Major Components**
*(Source: FEV, Inc.)*

As seen in **Table 4.6-3**, there are three sub-subsystems that make up the Front Suspension Subsystem: the front suspension links/arms upper and lower, front suspension knuckle assembly, and the front stabilizer (anti-roll) bar assembly. The most significant contributor to the mass within this subsystem was found to be within the front suspension links/arms upper and lower (approximately 57.9%), then the front suspension knuckle assembly (approximately 28.0%), followed by the front stabilizer (anti-roll) bar assembly (approximately 14.1%).

**Table 4.6-3: Mass Breakdown by Sub-subsystem for the Front Suspension Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 04 | 01 | 00 | Front Suspension Subsystem | |
| 04 | 01 | 02 | Front Suspension Links/Arms Upper and Lower | 31.7 |
| 04 | 01 | 04 | Front Suspension Knuckle Assembly | 15.3 |
| 04 | 01 | 05 | Front Stabilizer (Anti-Roll) Bar Asm | 7.73 |
| | | | | |
| | | | Total Subsystem Mass = | 54.8 |
| | | | Total System Mass = | 301.2 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 18.2% |
| | | | System Mass Contribution Relative to Vehicle = | 2.23% |

#### 4.6.1.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado Front Suspension Subsystem (**Image 4.6-3**) follows typical industry standards for design and performance, which includes a focus on strength and durability with least material cost. The material of choice with most components is steel. Chevrolet also focuses on providing similar if not identical components across all platform variants to take advantage of economies of scale in minimizing production costs. However, this approach is not optimal for design efficiency based on applications nor does it allow for maximum weight-versus-performance efficiency.

The following is a brief introduction to the components of the Front Suspension Subsystem: The lower control arm assembly (**Image 4.6-4**) is an integrated design made up of the control arm (**Image 4.6-6**), two rubber isolators (with steel tube inserts) and a lower ball joint assembly (**Image 4.6-5**). The lower ball joint assembly is retained in the lower control arm and attaches to the lower portion of the steering knuckle. The steering knuckle (**Image 4.6-7**) is cast iron and precision machined. The upper control arm assembly (**Image 4.6-8**), like the lower control arm assembly, is an integrated design made up the upper control arm (**Image 4.6-10**), two bushing assemblies (with inner- and outer-spacers and a rubber isolator), and an upper ball joint assembly (**Image 4.6-9**). The upper ball joint assembly is retained in the upper control arm and attaches to the upper portion of the steering knuckle. The upper ball joint assembly components include the housing, spindle shaft, socket boot, retaining rings, and grease. The Stabilizer Bar System (**Image 4.6-11**) contains the stabilizer bar, bar mounts, mount bushings, and link assemblies. The stabilizer bar (**Image 4.6-13)** is a hollow steel tube bent into shape with pinched flanges and punched holes for mounting points. The stabilizer bar mounts (**Image 4.6-14**) are of standard stamped steel construction brackets. The stabilizer bar mount bushings (**Image 4.6-15**) are molded rubber isolators. The stabilizer link assemblies (**Image 4.6-16**) are made from multiple components, including a threaded steel rod with over-molded rubber, rubber isolators, and retaining fasteners.

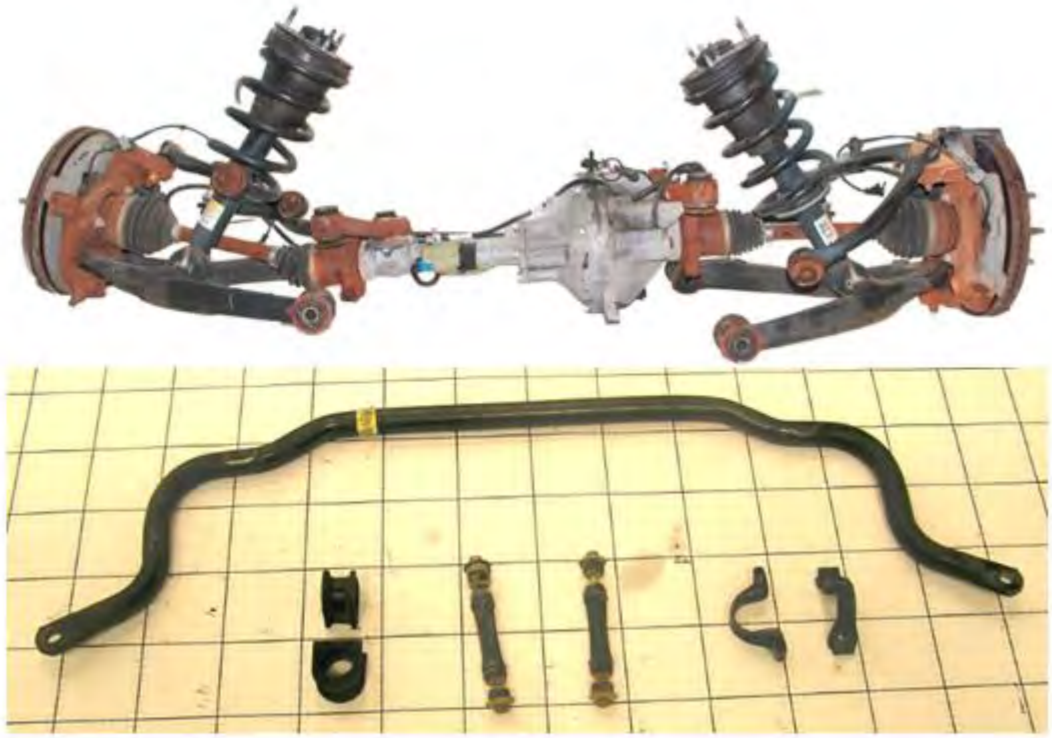


**Image 4.6-3: Front Suspension Subsystem Current Assembly**
*(Source: A2MAC1, top; and FEV, Inc., bottom)*

4.6.1.2.1 Lower Control Arm Assembly

The baseline OEM Chevrolet Silverado front lower control arm assembly (**Image 4.6-4)** is a cast iron construction with precision machining operations. The lower control arm assembly has a mass of 10.8 kg. This assembly consists of the following components: ball joint assembly and two rubber isolators (with steel tube inserts).

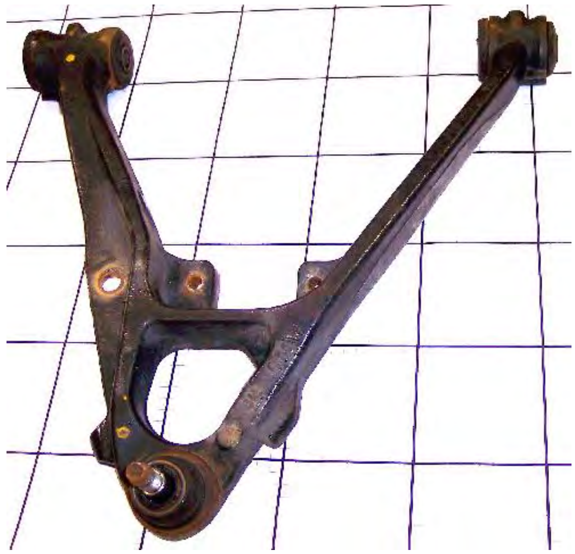


**Image 4.6-4: Lower Control Arm Assembly Current Assembly**
*(Source: FEV, Inc.)*

#### *4.6.1.2.1.1 Lower Ball Joint Assembly*

The baseline OEM Chevrolet Silverado lower ball joint assembly (**Image 4.6-5**) is a multi-piece design assembly. The spindle is forged steel, machined and assembled with various components including the socket boot, retaining rings, castle nut, and grease. The overall assembly has a mass of 0.580 kg.

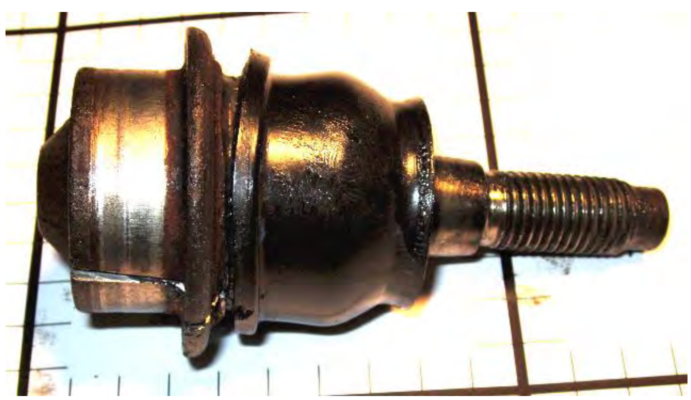


**Image 4.6-5: Lower Ball Joint Sub-assembly**
*(Source: FEV, Inc.)*

#### *4.6.1.2.1.2 Lower Control Arm*

The baseline OEM Chevrolet Silverado lower control arm (**Image 4.6-6**) is a cast iron part with precision machining operations performed to meet OEM specifications. The lower control arm has a mass of 9.55 kg. Control arms have traditionally been made from either welded steel assemblies or cast from iron. This allowed for adequate strength and component life without using more expensive processes or materials. Now, with advances in materials and processing methods, other cost-effective choices are available and are being utilized in aftermarket and high-performance applications as well as OEM vehicle markets. Included among these alternate mediums are aluminum, titanium, steel, magnesium, and metal matrix composites (MMC). Forming methods now include sand cast, semi-permanent metal molding, die casting, machining from billet, and welded fabrications.

**Image 4.6-6: Lower Control Arm Current Sub-Assembly**
*(Source: FEV, Inc.)*

While these alternatives are now designed with the strength and performance required, they do include a significant cost-versus-mass increase. However, the weight savings achieved is quite substantial and assists with reducing vehicle requirements for suspension loads, handling, ride quality, and engine horsepower requirements. Another advanced development includes using bulk molding compound with long, randomly oriented carbon fiber. This continues to be of interest due to the ability to easily mold it into complex shapes.

#### 4.6.1.2.2 Steering Knuckle

The baseline OEM Chevrolet Silverado steering knuckle (**Image 4.6-7**) is a single-piece, cast-iron knuckle of a standard design configuration and has a mass of 7.66 kg. Knuckles are historically made from cast iron for strength and function. Over the last several years, advances in alternative materials and processing methods have made new choices available. Rather than cast iron only, aluminum alloys are now common and are used in high-volume applications by many OEMs. This allows not only similar functional performance but substantial weight savings along with minimal, if any, cost increase.

**Image 4.6-7: Steering Knuckle Current Component**
*(Source: FEV, Inc.)*

#### 4.6.1.2.3 Upper Control Arm Assembly

The baseline OEM Chevrolet Silverado upper control arm assembly (**Image 4.6-8**) is a forged steel construction with precision machining operations to receive the bushing assemblies and the ball joint assembly. The upper control arm assembly has a mass of 3.30 kg. This assembly consists of the upper control arm, ball joint assembly, and two bushing assemblies (with inner- and outer-spacers and a rubber isolator).

**Image 4.6-8: Upper Control Arm Assembly Current Assembly**
*(Source: FEV, Inc.)*

*4.6.1.2.3.1 Upper Ball Joint Sub-Assembly*

The baseline OEM Chevrolet Silverado upper ball joint assembly (**Image 4.6-9**) is a multi-piece design assembly. The spindle is forged steel, machined, and assembled with various components including the socket boot, retaining rings, castle nut, and grease. The overall assembly has a mass of 0.580 kg. No other viable, high-volume manufactured alternate designs were found. Due to performance requirements for loading and strength, no cost-effective material substitutions were identified for replacement. Therefore, it was determined that a sizing and normalization activity would need to be performed based on gross vehicle weight (GVW) to see if any opportunities exist.

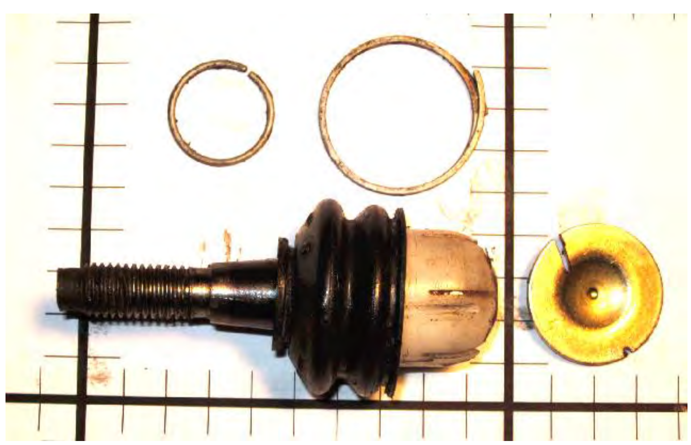


**Image 4.6-9: Upper Ball Joint Sub-assembly**
*(Source: FEV, Inc.)*

#### *4.6.1.2.3.2 Upper Control Arm*

The baseline OEM Chevrolet Silverado upper control arm (**Image 4.6-10**) is forged steel with precision machining operations performed to meet OEM specifications. The upper control arm has a mass of 2.28 kg. Control arms have traditionally been made from either welded steel assemblies, forgings, or cast from iron. This allowed for adequate strength and component life without using more expensive processes or materials. Now with advances in materials and processing methods, new cost-effective choices are available are being utilized in aftermarket and high-performance applications as well as OEM vehicle markets. Among some of these alternate mediums are aluminum, titanium, steel, magnesium, and metal matrix composites (MMC). Forming methods now include sand-cast, semi-permanent metal molding, die casting, machining from billet, and welded fabrications.

**Image 4.6-10: Upper Control Arm Current Sub-Assembly**
*(Source: FEV, Inc.)*

While these alternatives are now designed with the required strength and performance, they do add a significant cost-versus-mass increase. However, the weight savings achieved is quite substantial and assists with reducing vehicle requirements for suspension loads, handling, ride quality, and engine horsepower requirements. Another advanced development includes using bulk molding compound with long, randomly oriented carbon fiber. This continues to be of interest due to the ability to easily mold it into complex shapes.

#### 4.6.1.2.4 Stabilizer Bar System

The baseline OEM Chevrolet Silverado Stabilizer Bar System (**Image 4.6-11**) is standard design and construction. The front stabilizer bar system includes a hollow steel bar, molded rubber mount bushings, steel stamped brackets, steel and rubber stabilizer links, and miscellaneous fasteners. This system has an overall mass of 7.73 kg. The system has undergone some changes recently relative to design, materials, and processing. Steel bars, besides being hollow, are now being made using alternative materials. Mounting bushings are now being made with various plastics in order to increase rigidity and increase life. Brackets and mountings are made now from new cast, forged, and molded processes as well as utilizing new materials such as aluminum, titanium, magnesium, and fiber reinforced plastics.

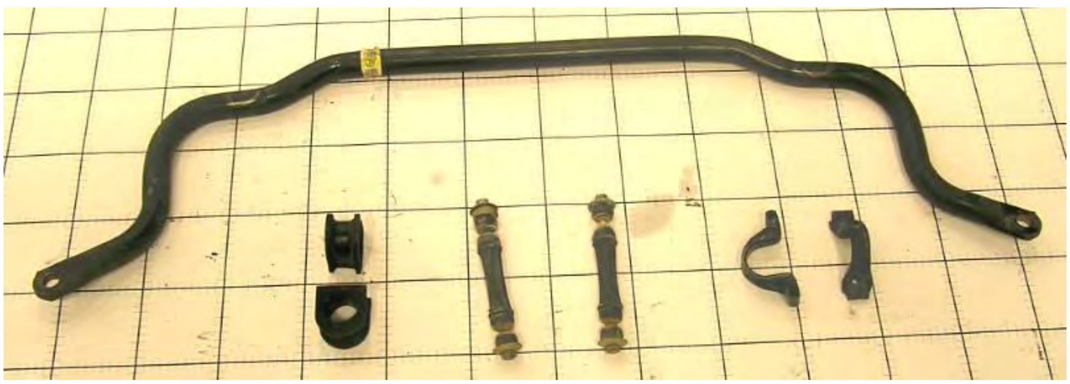


**Image 4.6-11: Stabilizer Bar System Current Component**
*(Source: FEV, Inc.)*

Another trend in suspension stabilization technology is the integration of more electronics. Electronic dampers allow a wide range between maximum and minimum damping levels and adjust instantly to ensure ride comfort and firm vehicle control. By integrating mechanical and electronic functions within the shock absorber system, automakers can improve handling and potentially reduce costs as technologies mature.

BMW has redesigned a standard suspension piece to resolve some past suspension problems. While roll bars or sway bars help control vehicle pitch, they are also a detriment to ride quality because they transmit vibrations from one side of a vehicle to the other.

To remedy this problem, BMW has developed Active Roll Stabilization (**Image 4.6-12**) for its 7-series vehicles. On these vehicles, roll bars have evolved into two-piece hydro-mechanical parts. Now, when one side of the vehicle noses sharply into a turn or drops down to meet the road, a hydraulic motor located between the bars turns the roll bar on the other side of the vehicle in a counter rotation motion, thereby keeping the entire vehicle flat.

Since the roll bar is separated into two pieces, vibrations from one side are not transmitted to the other. That allows the two sides of the vehicle to be truly independent. The result is a vehicle with improved handling and no trade-off in ride comfort while also allowing a potential reduction in vehicle front end mass.

**Image 4.6-12: BMW Active Roll Stabilization System**
*(Source: http://www.search-autoparts.com/searchautoparts/article/articleDetail.jsp?id=68222)*

### *4.6.1.2.4.1 Stabilizer Bar*

The baseline OEM Chevrolet Silverado front stabilizer bar (**Image 4.6-13**) is standard construction with a hollow steel bar bent into shape and pinched flanges with punched holes for mounting points. This bar has a mass of 6.52 kg. The stabilizer bar has been redesigned in recent years. Design, materials and processing changes now allow the use of alternative materials such as aluminum, titanium, hollow structural section (HSS), and fiber reinforced composites. While these materials can effect performance and handling under various conditions, significant mass savings can also be achieved.

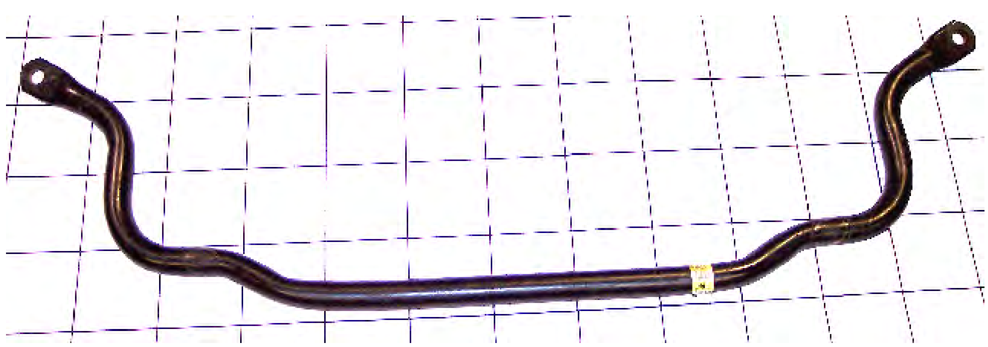


**Image 4.6-13: Front Stabilizer Bar Current Component**
*(Source: FEV, Inc.)*

#### *4.6.1.2.4.2 <u>Stabilizer Bar Mountings</u>*

The baseline OEM Chevrolet Silverado front stabilizer bar mountings (**Image 4.6-14**) is of standard construction. It has a mass of 0.230 kg. These brackets have had some changes in design, materials and processing recently. Various configurations include alternate materials for aluminum, magnesium, hollow structural sections (HSS), and plastics. Process variations for manufacturing include casting, molding, and forging.

**Image 4.6-14: Stabilizer Bar Mounting Current Components**
*(Source: FEV, Inc.)*

#### *4.6.1.2.4.3 <u>Stabilizer Bar Mount Bushings</u>*

The baseline OEM Chevrolet Silverado stabilizer bar mount bushings (**Image 4.6-15**) are of standard design made of molded rubber. They have a mass of 0.078 kg. Mounting bushings have recently had some changes in design, materials, or processing. Most changes are in material differences; it is now common that nylons and urethanes are used by many OEMs and nearly all aftermarket manufacturers. While there is a minimal accomplishment in mass savings, there is a cost savings and a realized functional performance enhancement.

**Image 4.6-15: Stabilizer Bar Mount Bushing Current Components**
*(Source: http://www.wundercarparts.com)*

### *4.6.1.2.4.4 Stabilizer Link Sub-Assembly*

The baseline OEM Chevrolet Silverado stabilizer link sub-assembly is standard steel and rubber construction with a mass of 0.238 kg. This link assembly (**Image 4.6-16**) has had little change in design, materials, or processing in recent years. Some alternative materials, however, are being used by manufacturers.

**Image 4.6-16: Stabilizer Link Current Sub-Assembly**
*(Source: FEV, Inc.)*

### 4.6.1.3 Mass Reduction Industry Trends

Automakers are deploying a wide variety of low-mass materials in new vehicle models on all subsystems including front suspension systems. Implementations have been documented showing reduced component mass for the same functionality using alternative materials like high-strength steel, aluminum, magnesium, plastics and polymer composites. Also, some notable ventures are into limited applications of magnesium, long fiber polymer composites, and, in rare cases, carbon fiber, and titanium.

The Chevrolet Silverado front suspension system is a "double wishbone" design that is considered to have superior dynamic characteristics as well as load-handling capabilities. The double wishbone suspension is often referred to as a double "A" arm or short long arm (SLA) suspension. The double wishbone design is commonly used in sports cars, luxury cars, and light trucks. Double wishbone designs allow the engineer to easily control wheel motion throughout suspension travel and work out the loads which different parts will bear. This allows the design of more optimized lightweight parts.

Design approaches for lightweighting the active components of the front suspension system are primarily focused on high-strength steels (i.e., coil springs) and high-strength aluminum (i.e., control arms). The progress has been slow over the years because of the typically higher resultant costs compared to non-high-strength steels. However, recent studies have shown cost comparisons near parity with well-designed parts using alternate materials, primarily high-strength steel.

Another significant consideration is how the secondary mass reduction effects weight reductions for all other vehicle subsystems. Less total vehicle mass reduces the suspension loading, which provides opportunities to further reduce suspension mass.

During the last decade, basalt fiber has emerged as a contender in the fiber reinforcement of composites. Proponents of this technology claim their products offer performance similar to S-2 glass fibers at a price point between S-2 glass and E-glass, and may offer manufacturers a less expensive alternative to carbon fiber for products in which the latter represents over-engineering and much higher cost.

Another technology that bears watching is bulk compound molding using polymer material filled with long carbon fiber.

Applications of basalt fiber and bulk-molded carbon fiber will be delayed indefinitely because of limited production capacity. However, the continental United States has very large deposits of basalt, such as the upper peninsula of Michigan. Basalt fiber research, production, and most marketing efforts are based in countries once aligned with the Soviet bloc. Companies currently involved in production and marketing include Kamenny Vek (Dubna, Russia); Technobasalt (Kyiv, Ukraine); Hengdian Group Shanghai Russia & Gold Basalt Fibre Co. (Shanghai, China); OJSC Research Institute Glassplastics and Fiber (Bucha, Ukraine); Basaltex, a division of Masureel Holding (Wevelgem, Belgium); Sudaglass Fiber Technology Inc. (Houston, Texas); and Allied Composite Technologies LLC (Rochester Hills, Michigan).

Carbon fiber is also becoming increasingly popular here in the U.S. The 2013 SRT Viper and the 2014 Chevrolet Corvette have carbon fiber hoods. The Corvette's production could exceed 20,000 units this year. The cost of carbon fiber is estimated to be around \$10 to \$15 per pound. For large components, such as the Viper and Corvette hoods, the process is very long to make these parts relative to typical high-volume cycle times. The relatively slow pre-preg technique used for making large parts is ill-suited to produce the complex shapes required for structural components. One alternative method for making structural carbon fiber parts is the less expensive resin transfer molding process. With resin transfer molding, the carbon fiber fabric is placed in a heated mold, and resin is injected into the mold under high pressure. This method reduces the production time for a component to usually less than 10 minutes.

Carbon fiber is clearly an up-and-coming material that all of Detroit's automakers are looking to expand the use of into many different applications. One such part examined for this report is the road wheel. According to Motor Authority, carbon fiber wheels are being produced for a high-end vehicle that comes with a total stated price of $15,000.[43] Regardless, GM formed a partnership with Teijin Ltd. of Japan to develop carbon fiber composites for high-volume vehicles. In April 2012, Ford Motor Co. and Dow Chemical Co. also announced a joint development agreement to establish an economical source of automotive-grade carbon fiber and develop component manufacturing methods for high-volume automotive applications.

#### 4.6.1.4 Summary of Mass Reduction Concepts Considered

The brainstorming activities generated the potential ideas as shown in **Table 4.6-4** for the Front Suspension Subsystem and its various components. The majority of these mass reduction ideas offer alternatives to traditional steel and include part modifications, material substitutions, processing, and fabrication differences, and use of alternative parts currently in production and used on other vehicles and applications. In our team approach to idea selection, we used judgment from extensive experience and research to prepare a list of the most promising ideas.

43 http://www.motorauthority.com/news/1081342_carbon-fiber-wheels-a-costly-upgrade-but-better-performance

**Table 4.6-4: Summary of Mass Reduction Concepts Initially Considered for the Front Suspension Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Front Suspension Subsystem** | | | |
| Upper Control Arm | Make out of cast aluminum | 40-50% wt save | 20-30% cost increase |
| | Make out of forged aluminum | 40-50% wt save | 20-30% cost increase |
| | Make out of welded titanium tubing | 20-25% wt save | 8-9x cost increase |
| | Make out of cast steel | < 1% wt save | Weaker control arm |
| | Replace from 2012 Dodge Durango | 15-20% wt save | 15-20% cost increase |
| | Make out of cast magnesium | 40-50% wt save | 15-20% cost increase |
| | Make out of stamped steel | 15-20% wt increase | 15-20% cost save |
| | Make out of Dupont plastic | 40-50% wt save | Stil in development |
| Lower Control Arm | Make out of cast aluminum | 40-50% wt save | 20-30% cost increase |
| | Make out of forged aluminum | 40-50% wt save | 20-30% cost increase |
| | Make out of welded titanium tubing | 20-25% wt save | 8-9x cost increase |
| | Make out of cast steel | < 1% wt save | Weaker control arm |
| | Replace from 2007 Ford F-150 | 15-20% wt save | 15-20% cost increase |
| | Make out of Dupont plastic | 40-50% wt save | Stil in development |
| Lower Control Arm Bushing | Make bushing spacer (long) out of aluminum | 40-50% wt save | 15-20% cost increase |
| | Make bushing spacer (long) out of plastic | 40-50% wt save | 100% cost increase |
| | Make rubber isolator (long) out of nylon | <5% wt save | 5-10% cost save |
| | Combine aluminum spacer & nylon isolator | 30-40% wt save | 10-15% cost increase |
| | Combine plastic spacer & nylon isolator | 30-40% wt save | 20-30% cost increase |

**Table 4.6-4 continued on next page**

**Table 4.6-4 (Cont'd): Summary of Mass Reduction Concepts Initially Considered for the Front Suspension Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Front Suspension Subsystem Continued** | | | |
| Upper Control Arm Bushing | Make inner bushing spacer out of aluminum | 40-50% wt save | 20-30% cost increase |
| | Make outer bushing spacer out of aluminum | 40-50% wt save | 20-30% cost increase |
| | Make rubber isolator out of nylon | < 5% wt save | 5-10% cost save |
| | Combine two aluminum spacers & nylon isolator | 40-50% wt save | 20-30% cost increase |
| Ball Joint | Replace upper ball joint from 2012 Dodge Durango | 5-10% wt save | 5-10% cost save |
| | Investigate lighter ball joint in A2MAC1 | 5-10% wt save | No lighter ball joint was found in the Silverado vehicle class |
| Knuckle | Make out of forged aluminum | 40-50% wt save | 20-30% cost increase |
| | Make out of cast aluminum | 40-50% wt save | 20-30% cost increase |
| | Make out of forged steel | <5% wt save | Stronger control arm 10% cost increase |
| | Replace from 2006 Dodge Ram | 20-25% wt save | 75-100% cost increase |
| Stabilizer Bar | Make out of solid aluminum bar | 20-25% wt save | 50-75% cost increase |
| | Make out of hollow aluminum bar | 40-50% wt save | 20-30% cost increase |
| | Make out of welded titanium tubing | 20-25% wt save | 5-6x cost increase |
| | Make out of glass/epoxy filament winding (solid) | 40-50% wt save | 5-6x cost increase |
| | Make out of carbon/epoxy filament winding (solid) | 70-80% wt save | 15-20% cost increase |
| | Replace from 2012 GMC Sierra | <2% wt save | <2% cost save |

**Table 4.6-4 continued next page**

**Table 4.6-4 (Cont'd): Summary of Mass Reduction Concepts Initially Considered for the Front Suspension Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Front Suspension Subsystem Continued** | | | |
| Stabilizer Bar Mounts | Make out of cast aluminum | 70-80% wt save | 20-30% cost increase |
| | Make out of stamped aluminum | 70-80% wt save | 20-30% cost increase |
| | Make out of cast magnesium | 20-25% wt save | 7-8x cost increase |
| | Make out of poly reinforced material | 60-70% wt save | 2-3x cost increase |
| | Remove (1) fastener w/hook feature | 10-15% wt save | 10-15% cost save |
| | Combine cast aluminum & hook feature | 60-70% wt save | 30-40% cost save |
| | Combine stamped aluminum & hook feature | 60-70% wt save | 30-40% cost save |
| | Combine cast magnesium & hook feature | 10-15% wt save | 6-7x cost increase |
| | Combine poly reinforced brkt & hook feature | 10-15% wt save | 6-7x cost increase |
| | | | |
| Stabilizer Bar Bushings | Make out of ylon | 5-10% wt save | 5-10% cost save |

### 4.6.1.5 Selection of Mass Reduction Ideas

**Table 4.6-5** shows a subset of the ideas generated from the brainstorming activities that were selected for detailed evaluation of both the achieved mass savings and the cost to manufacture. Several ideas suggest alternative materials as well as part substitutions from other vehicle designs.

**Table 4.6-5: Mass Reduction Ideas Selected for the Detailed Front Suspension Subsystem Analysis**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|---|---|---|
| **04** | **01** | **00** | **Front Suspension Subsystem** | |
| 04 | 01 | 00 | Upper Control Arms | Normalize & make out of cast magnesium |
| | | | | |
| 04 | 01 | 00 | Lower Control Arms | Make out of forged aluminum |
| | | | | |
| 04 | 01 | 00 | Lower Control Arm Bushing (Long) | Make spacer out of plastic and bushing out of nylon |
| | | | | |
| 04 | 01 | 00 | Lower Control Arm Bushing (Short) | Make spacer out of plastic and bushing out of nylon |
| | | | | |
| 04 | 01 | 00 | Upper Control Arm Bushing | Make spacers out of aluminum and bushing out of nylon |
| | | | | |
| 04 | 01 | 00 | Upper Ball joint | Normalize upper ball joint |
| | | | | |
| 04 | 01 | 00 | Knuckle | Normalize & make out of cast aluminum |
| | | | | |
| 04 | 01 | 00 | Stabilizer Bar Mount | Make out of stamped aluminum & remove (1) fastener w/hook feature |
| | | | | |
| 04 | 01 | 00 | Stabilizer Bushings | Make bushing out of nylon |

The new mass-reduced Front Suspension System (**Image 4.6-17**) configuration is still that of typical vehicle design utilized by nearly all OEMs. The reductions in mass achieved were accomplished by improving and replacing individual sub-assemblies and components. The overall design and function remains the same thus eliminating drastic revisions causing significant vehicle interface redesigns.

**Image 4.6-17: Front Suspension Mass Reduced System**
*(Source http://www.fabtechmotorsports.com/products/uploads/image/susp-1/AArmCoilover2WD4WD.jpg)*

#### 4.6.1.5.1 Lower Control Arm Assembly

The solutions chosen to be implemented on the lower control arm assembly (**Image 4.6-18**) were the combination of a few ideas affecting the bushing assembly and the lower control arm. The total mass of this new sub-assembly is 6.06 kg compared to the baseline mass of 10.8 kg. These ideas included modifications to design, materials utilized, and processing methods used to manufacture the lower control arm bushing assembly and the lower control arm. The lower control arm assembly is made up of a control arm, ball joint, and rubber isolator (with an inner spacer).

**Image 4.6-18: Lower Control Arm Mass Reduced Assembly**
*(Source: http://www.1aauto.com/content/articles/control-arms)*

It should be noted that as late as 2009, General Motors offered two XFE (eXtra Fuel Economy) models for the Chevrolet Silverado and GMC Sierra which included the aluminum version of the 5.3L V-8, with Active Fuel Management (cylinder deactivation), six-speed automatic transmission, low rolling resistance tires, 17-inch aluminum wheels, and aluminum lower control arms. The aluminum control arms were eventually switched back to cast iron due to cost reduction efforts. The 2014 Silverado comes equipped with aluminum control arms and aluminum knuckles.

Additionally, Raufoss Technology, a privately held corporation fully owned by Neuman Aluminum, has developed the aluminum lightweighting techniques, PreFormForge® and ExtruForm®. These processes are used for lightweighting suspension components such as the rear lower control arm assembly shown in **Image 4.6-19**.

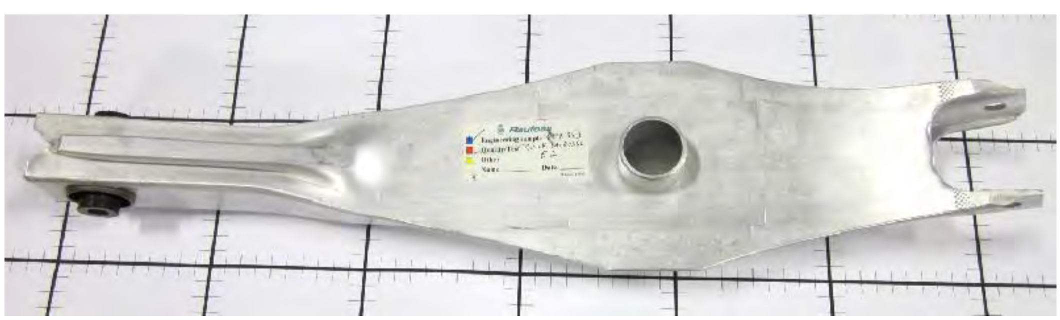


**Image 4.6-19: Buick Lacrosse Rear Control Arm**
*(Source: FEV, Inc.)*

#### *4.6.1.5.1.1 Lower Control Arm Bushing Assembly*

The new lower control arm bushing assembly (**Image 4.6-20**) is still a multi-piece design, with the spacer components now being made from aluminum instead of steel. This new design utilizes aluminum for the inner bushing spacer and the bushing material is now made from nylon. The long bushing assembly has a redesigned total mass of 0.230 kg versus 0.390 kg for the baseline design and a redesigned total mass of 0.178 kg for the short bushing assembly versus the baseline design of 0.303 kg.

**Image 4.6-20: Lower Control Arm Bushing Mass Reduced Assembly**
*(Source:http://www.kseriesparts.com/merchant.mvc)*

The weight savings achieved is quite substantial and assists with reducing vehicle requirements for suspension loads, handling, ride quality, and engine horsepower requirements. Consideration must still be given to adequate validation testing to fit this solution to particular vehicle requirements.

#### *4.6.1.5.1.2 Lower Control Arm*

Traditionally, control arms have been made from either welded steel assemblies or cast from iron. This allowed for adequate strength and component life without using more expensive processes or materials. Now, with advances in materials and processing methods, other choices are available that have become more cost effective and are often being utilized in aftermarket and by OEMs. Among some of these alternate mediums include aluminum, titanium, steel, and magnesium. Forming methods now include sand cast, semi-permanent metal molding, die casting, machining from billet, and welded fabrications.

The idea implemented for the lower control arm (**Image 4.6-21**) is to make the arm out of forged aluminum. The redesigned lower control arm has a new net mass of 5.10 kg compared to the baseline mass of 9.55 kg.

**Image 4.6-21: Lower Control Arm Mass Reduced**
*(Source: http://www.bing.com/images/search?q=2009+silverado+xfe+lower+control+arm)*

A 2009 Chevrolet Silverado lower control arm shown **Image 4.6-22**) has a known mass of 5.74 kg.

**Image 4.6-22: 2009 Chevrolet Silverado Lower Control Arm Aluminum Forging**
*(Source: FEV, Inc.)*

#### 4.6.1.5.2 Upper Control Arm Assembly

The solutions chosen to be implemented on the upper control arm assembly (**Image 4.6-23**) was the combination of multiple ideas across several different components. The total mass of this new assembly is 1.64 kg compared to the baseline mass of 3.44 kg. These ideas included modifications to design, materials utilized, and processing methods required for the upper ball joint, upper control arm, and the upper control arm bushing assemblies. The redesigned upper control arm will be made from cast magnesium with a chemical conversion coating to prevent corrosion and dissimilar material interactions. The upper control arm bushing assembly is made up of an inner bushing spacer, outer bushing spacer, and an isolator bushing. The redesigned bushing assembly will have the inner and outer spacers made from aluminum and the isolator molded out of nylon. The balljoint assembly will be normalized to the 2012 Dodge Durango.

**Image 4.6-23: Upper Control Arm Mass Reduced Assembly**
*(Source: http://i.ebayimg.com/t/02-05-Dodge-Ram-1500-Front-Upper-Control-Arm-Lower-Ball-Joint-Kit)*

A potential for further mass reduction of the upper control arm is with a material produced and distributed by SABIC's Innovative Plastics business called LNP™ VERTON™ compound. In **Figure 4.6-2**, a VERTON plastic-metal hybrid control arm was modeled by SABIC and compared to a known aluminum control arm. The mass savings opportunity is estimated to be approximately 30-40% lighter than the aluminum version.


**Figure 4.6-2: SABIC Lower Control Arm**
*(Source: SABIC)*

Another technology successfully applied to lightweighting control arms is with Forged Composite® technology, which is an advanced compression molding technique that uses a synthetic composite material supplied by Quantum Composites and produced in an alliance between Lamborghini and Callaway Golf Company in which bundles of microscopic carbon fibers held together in a resin that is compressed to make almost any shape. As seen in **Image 4.6-24**, the lower control arm for the Lamborghini Sesto Elemento uses this new technology to reduce the mass of its front and rear upper and lower control arms.

**Image 4.6-24: Lamborghini Sesto Elemento Front Lower Control Arm**
*(Source: http://www.lambolab.org/wp-content/uploads/03research/pub/05chop/2011-ASC-montreal-forged-suspens-ICE.pdf)*

*4.6.1.5.2.1* <u>*Upper Ball Joint Sub-Assembly*</u>

The solution used for the ball joint assembly (**Image 4.6-25**) is a sub-assembly substitution from the 2012 Durango application. No other viable high-volume manufactured alternate design substitutions were found. Due to performance requirements for loading and strength, no cost-effective materials were identified for replacement. Therefore, it was determined that a sizing and normalization activity would be applied based on GVW. The overall sub-assembly has a replacement mass of 0.529 kg versus the baseline mass of 0.580 kg.

**Image 4.6-25: Front Ball Joint Mass Reduced Sub-assembly**
*(Source: http://www.autopartswarehouse.com/shop_parts/ball_joint/dodge/durango.html)*

#### *4.6.1.5.2.2 Upper Control Arm*

Control arms have traditionally been made from either welded steel assemblies or cast from iron. This allowed for adequate strength and component life without using more expensive processes or materials. Now, with advances in materials and processing methods, other choices are available that have become more cost effective and are often being utilized in aftermarket and by OEMs. Among some of these alternate mediums are aluminum, titanium, steel, and magnesium. Forming methods now include sand cast, semi-permanent metal molding, die casting, machining from billet, and welded fabrications. The idea implemented for the upper control arm (**Image 4.6-23**) was to make the arm out of cast magnesium with a chemical conversion coating to prevent corrosion and dissimilar material interactions. Although magnesium was not selected for the lower control arm, it was selected for the upper control arm because of the weight savings opportunity. Also, magnesium was chosen due to the reduced forces acting on the upper control arm compared to the lower control arm. The new arm has a net mass of 0.759 kg while the baseline control arm is 2.28 kg.

#### *4.6.1.5.2.3 Upper Control Arm Bushing Assembly*

The new upper control arm bushing assembly (**Image 4.6-26**) is still a multi-piece assembly, with the components now made from aluminum. This design utilizes aluminum for the inner and outer bushing spacer, and the bushing is made from nylon. This new assembly has a total mass of 0.174 kg compared to the baseline assembly mass of 0.289 kg.

**Image 4.6-26: Upper Control Arm Bushing Mass Reduced Assembly**
*(Source:http://www.bing.com/images/search?q=upper+control+arm+bushing+assembly)*

The weight savings achieved assists with reducing vehicle requirements for suspension loads, handling, ride quality, and engine horsepower requirements. Consideration must still be given to adequate validation testing to fit this solution to particular vehicle requirements.

#### 4.6.1.5.3 Steering Knuckle

The new steering knuckle (**Image 4.6-27**) is a component substitution from the 2012 GMC Sierra application. In addition, the material will also be changed from steel to aluminum. Due to replacing the steel with aluminum, an additional material volume of 40% was required. Aluminum alloys are now a common choice, used in high-volume applications by many OEMs including GM, BMW, Audi, Honda, Toyota, Ford, and Chrysler. Due to performance requirements for loading and strength, proper validation testing would be required dependent upon the application. Therefore, it was determined that a sizing and normalization activity would be applied based on GVW. The redesigned knuckle has a replacement mass of 3.73 kg versus the baseline mass of 7.67 kg.

**Image 4.6-27: Steering Knuckle Mass Reduced Component**
*(Source: FEV, Inc.)*

### 4.6.1.5.4 Stabilizer Bar System

The proposed stabilizer bar system (**Image 4.6-28**) is of standard configuration, although with a different design and construction. Rather than being composed of a solid steel forged bar with molded rubber mount bushings and steel stamped brackets, it is still the same baseline stabilizer bar, but with cast aluminum mounting brackets and nylon bushings. Together, this new system has a reduced mass totaling 7.43 kg versus the baseline system of 7.73 kg.

**Image 4.6-28: Stabilizer Bar System Mass Reduced System**
*(Source: http://a248.e.akamai.net/origin-cdn.volusion.com/gcme7.tr5v2/v/vspfiles/photos/)*

#### *4.6.1.5.4.1 Stabilizer Bar Mountings*

The new stabilizer bar mounting brackets (Error! Reference source not found.**29**) are now ade of die-cast aluminum. Due to the replacement of steel with aluminum, an additional material volume savings of 50% was required. The mountings have an individual mass of 0.120 kg compared to the baseline mass of 0.230 kg.

These brackets were designed with a hook feature, thus eliminating one fastener per bracket. These brackets have progressed with changes in design, materials, and processing. These designs include alternate materials for aluminum, magnesium, hollow structural section (HSS), and fiber plastics. Process variations for manufacturing include casting, molding, and forging.

**Image 4.6-29: Stabilizer Bar Mounting Mass Reduced Component**
*(Source: http://store.vacmotorsports.com/beastpower----e39-rear-sway-bar-brackets-p2410.aspx)*

#### *4.6.1.5.4.2 Front Stabilizer Bar Mount Bushings*

The redesigned front stabilizer bar mount bushings (**Image 4.6-30**) are of standard design, but utilize an alternate material of nylon as opposed to rubber. The new bushings have a mass of 0.067 kg compared to the baseline mass of 0.078 kg.

Many aftermarket and OEM manufacturers now utilize this new material choice for many vehicle applications. This is due to improved handling performance, increase component life, and even a small amount of mass reduction.

**Image 4.6-30: Stabilizer Bar Mount Bushing Mass-Reduced Component**
*(Source: http://www.suspensionconnection.com/cgi-bin/suscon/18-1116.html)*

### 4.6.1.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.6-6** shows the results of the mass reduction ideas that were evaluated for the Front Suspension Subsystem. This resulted in a subsystem overall mass savings of 21.3 kg and a cost hit differential of $23.71.

**Table 4.6-6: Mass Reduction and Cost Impact for the Front Suspension Subsystem**

| | | | | Net Value of Mass Reduction Ideas | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys/ Sub-Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | | | | | | | |
| 04 | 01 | 00 | Front Suspension | | | | | | |
| 04 | 01 | 02 | Front Suspension Links/Arms Upper and Lower | B | 13.1 | -$10.99 | -$0.84 | 41.4% | 0.54% |
| 04 | 01 | 03 | Front Suspension Knuckle Assembly | C | 7.89 | -$12.07 | -$1.53 | 51.4% | 0.32% |
| 04 | 01 | 04 | Front Stabilizer Bar Asm | C | 0.300 | -$0.65 | -$2.16 | 3.9% | 0.01% |
| | | | | | | | | | |
| | | | | C | 21.3 (Decrease) | -$23.71 (Increase) | -$1.11 (Increase) | 38.9% | 0.87% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.6.2 Rear Suspension Subsystem

#### 4.6.2.1 Subsystem Content Overview

**Image 4.6-31** represents the major suspension components in the Rear Suspension Subsystem and their relative location and position relevant to one another as located on the vehicle rear end.

**Image 4.6-31: Rear Suspension Subsystem**
*(Source: A2MAC1)*

As seen in **Image 4.6-32**, the Rear Suspension Subsystem consists of the major components of the leaf spring assembly: leaf springs, leaf spring bushings, shackle bracket, shackle bracket bushings, saddle bracket, spacer blocks, U-bolts, and miscellaneous attaching components.

**Image 4.6-32: Rear Suspension Subsystem Current Major Components**
*(Source: FEV, Inc.)*

As seen in **Table 4.6-7**, the single sub-subsystem that makes up the Rear Suspension Subsystem is the Rear Road Springs.

**Table 4.6-7: Mass Breakdown by Sub-subsystem for the Rear Suspension Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 04 | 02 | 00 | Rear Suspension Subsystem | |
| 04 | 02 | 01 | Rear Road Springs | 63.5 |
| | | | | |
| | | | Total Subsystem Mass = | 63.5 |
| | | | Total System Mass = | 301.2 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 21.1% |
| | | | System Mass Contribution Relative to Vehicle = | 2.59% |

#### 4.6.2.2 Chevrolet Silverado Baseline Subsystem Technology

As with the front suspension, the Chevrolet Silverado's Rear Suspension System follows typical industry standards. See **Section 4.6.1.2** for additional front suspension information.

The Chevrolet Silverado's Rear Suspension Subsystem (**Image 4.6-33**) follows typical industry standards for design and performance. This includes a focus on strength and durability with least material cost. Steel is the material of choice with most components. Chevrolet also focuses on providing similar, if not identical, components across all platform variants to take advantage of economies of scale in minimizing production costs. However, this approach is not optimal for design efficiency based on applications and does not allow for maximum weight versus performance efficiency.

A brief introduction to the components of the Rear Suspension Subsystem: The rear leaf spring assembly (**Image 4.6-34**) is a standard steel fabrication with three leaf springs (base, middle, and upper) stacked together with attachment points at each end of the upper leaf spring. The leaf spring bushing assembly (**Image 4.6-35**) is a molded rubber isolator with a rolled steel sleeve in the center and is encapsulated with a thin steel outer tube. There are two different sized bushing assemblies: 2.75" diameter for the front bushing assembly and 2.50" diameter for the rear bushing assembly. The shackle bracket assembly (**Image 4.6-36**) attaches to the rear end portion of the leaf spring assembly and connects the leaf spring assembly to the vehicle frame. The shackle bracket (**Image 4.6-37**) is a steel stamping with a rolled end to receive the shackle bracket bushing. The shackle bracket bushing (**Image 4.6-38**) is a molded rubber isolator with a rolled steel sleeve inserted into the center of the bushing. The saddle bracket (**Image 4.6-39**) is a steel stamping that locates on the bottom of the rear axle and receives the U-bolts, which clamp the leaf spring assembly to the rear axle. The spacer blocks (**Image 4.6-33**) spaces the leaf spring assembly to the OEM specified height. The spacer is clamped in place between the leaf spring assembly and the top of the rear axle. The U-bolts are specially formed fasteners that clamp the leaf spring assembly to the rear axle. The spring bumper is a molded stop that limits the amount of travel the rear axle can move by hitting the end of the bumper.

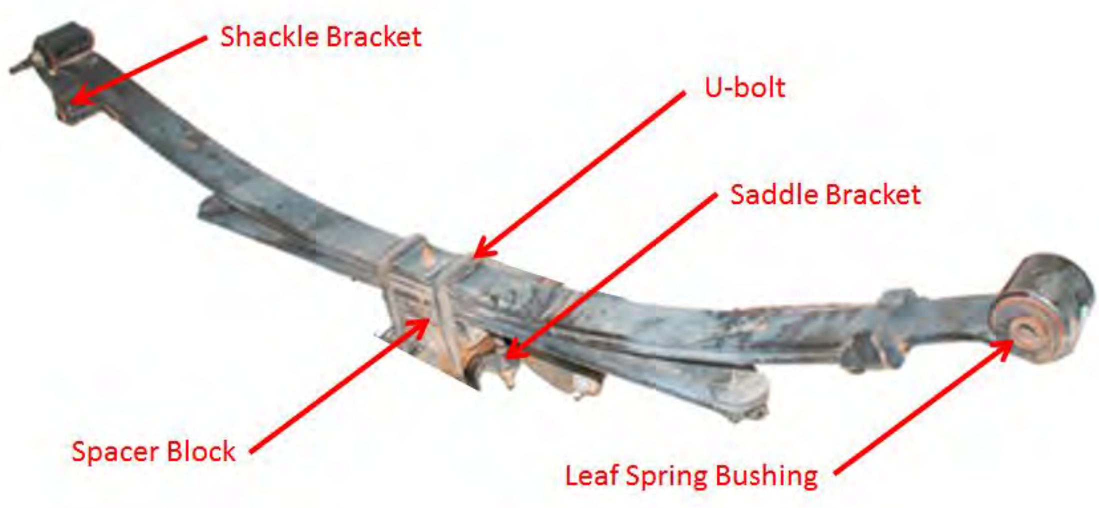



**Image 4.6-33: Rear Suspension Subsystem Current Assembly**
*(Source: A2MAC1)*

4.6.2.2.1 <u>Rear Leaf Spring Assembly</u>

The baseline OEM Chevrolet Silverado Rear Leaf Spring Assembly, **Image 4.6-34**, is a multi-piece assembly, with the major portions being made from steel bar stock. The total mass of this assembly is 26.2 kg. This assembly also consists of two rubber isolators with inner and outer metal sleeves.

**Image 4.6-34: Rear Leaf Spring Current Assembly**
*(Source: FEV, Inc.)*

#### 4.6.2.2.2 Front and Rear Leaf Spring Bushing Assembly

The baseline OEM Chevrolet Silverado leaf spring bushing assembly (**Image 4.6-35**) is a multi-piece assembly, with the isolator portion being made from molded rubber. The inner sleeve is a steel rolled tube while the outer sleeve is a steel stamped housing. The front overall assembly has a mass of 0.439 kg, while the rear assembly has 0.342 kg.

**Image 4.6-35: Front and Rear Leaf Spring Bushing Current Assembly**
*(Source: FEV, Inc.)*

#### 4.6.2.2.3 Shackle Bracket Assembly

The baseline OEM Chevrolet Silverado Shackle Bracket Assembly (**Image 4.6-36**) includes a steel stamping with a rolled end to receive the shackle bracket bushing. This unit has a total mass of 0.845 kg.

**Image 4.6-36: Shackle Bracket Current Assembly**
*(Source: FEV, Inc.)*

4.6.2.2.4 Shackle Bracket

The baseline OEM Chevrolet Silverado Shackle Bracket (**Image 4.6-37**) is a steel stamping with a rolled end to receive the shackle bracket bushing and has a mass of 0.648 kg.

**Image 4.6-37: Shackle Bracket Current Component**
*(Source: FEV, Inc.)*

#### 4.6.2.2.5 Shackle Bracket Bushing Assembly

The baseline OEM Chevrolet Silverado Shackle Bracket Bushing Assembly (**Image 4.6-38**) is a molded rubber isolator with a rolled steel sleeve inserted into the center of the bushing and has a mass of 0.197 kg. Sleeves are historically made from rolled steel sheet for strength and function. Over the last several years, advances in alternative materials and processing methods have made new choices available. Rather than steel only, aluminum alloys are now a common choice and are used in high-volume applications by many OEMs. This allows not only similar functional performance but substantial weight savings along with minimal, if any, cost increase.

**Image 4.6-38: Shackle Bracket Bushing Assembly Current Component**
*(Source: FEV, Inc.)*

#### 4.6.2.2.6 Saddle Bracket

The baseline OEM Chevrolet Silverado Saddle Bracket (**Image 4.6-39**) is standard design and construction composed from stamped sheet steel. It has a mass of 1.30 kg.

**Image 4.6-39: Saddle Bracket Current Component Example**
*(Source: FEV, Inc.)*

#### 4.6.2.2.7 Spacer Block

The baseline OEM Chevrolet Silverado spacer block (**Image 4.6-40**) is standard design and construction composed from cast iron. It has a mass of 1.51 kg.

**Image 4.6-40: Spacer Block Current Component Example**
*(Source: FEV, Inc.)*

### 4.6.2.3 Mass Reduction Industry Trends

Automakers are deploying a wide variety of low-mass materials in new vehicle models regarding all subsystems including suspensions. Implementations have been documented showing reduced component mass for the same functionality using alternative materials such as high-strength steel, aluminum, magnesium, plastics, and polymer composites. Also, some notable ventures are into limited applications of magnesium, long fiber polymer composites, and, in rare cases, carbon fiber and titanium.

Design approaches for lightweighting the active components of the Rear Suspension System are primarily focused on higher strength steels (i.e., leaf springs) and high strength aluminum (i.e., control arms). The progress has been slow over the years because of the typically higher resultant costs relative to non-high strength steels. However, recent studies have shown cost comparisons near parity with well-designed parts using alternate materials, primarily high-strength steel.

Another significant mass reduction opportunity exists in the Rear Suspension System – namely the leaf spring assembly. Traditional steel leaf springs are rectangular shape and can be multi-stacked in order to obtain the desired spring load. Although there have been advances in steel leaf spring design that have reduced the mass, they pale in comparison to the mass savings opportunity that composites offer.

Glass fiber reinforced plastic (GFRP) leaf springs are used extensively in Europe and in the U.S. on heavy-duty trucks and trailers. They are typically made from a glass fiber fabric that is laminated and bonded by a polyester resin. The fiber strands are soaked with resin and then wrapped together using a filament winding process and then squeezed together under pressure to obtain the final shape.

LITEFLEX® LLC, a manufacturer of OEM composite leaf springs, has supplied composite leaf springs since 1998 to support production requirements on the Sprinter commercial vehicles, namely the NCV3 Sprinter. Other customers using Liteflex composite leafs springs are the GM Corvette and Land Rover. Liteflex also produces composite leaf springs for heavy duty truck applications for Kenworth, Peterbilt, Freightliner, and International.

According to Senthilkumar Mouleeswaran, in his report *Design, Manufacturing and Testing of Polymer Composite Multi-Leaf Spring for Light Passenger Automobiles – A Review*: "From the design and experimental fatigue analysis of composite multi-leaf spring using glass fiber reinforced polymer are carried out using data analysis, it is found that the composite leaf spring is found to have 67.35% lesser stress, 64.95% higher stiffness and 126.98% higher natural frequency than that of existing leaf spring. The conventional multi leaf spring weighs about 13.5 kg whereas the E-glass/Epoxy multi leaf spring weighs only 4.3 kg. Thus the weight reduction of 65.15% is achieved. Besides the reduction of weigh, the fatigue life of composite leaf spring is predicted to be higher than that of steel leaf spring."[44]

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44*http://cdn.intechopen.com/pdfs/30353/InTechDesign_manufacturing_and_testing_of_polymer_composite_multi_leaf_spring_for_light_passenger_automobiles_a_review.pdf*:

Another significant consideration should be the secondary mass reduction effects - weight reductions for all other vehicle subsystems. Less total vehicle mass reduces the suspension loading and provides opportunities to further reduce suspension mass.

#### 4.6.2.4 Summary of Mass Reduction Concepts Considered

The brainstorming activities generated the ideas shown in **Table 4.6-6** for the Rear Suspension Subsystem and its various components. The majority of these mass reduction ideas offer alternatives to steel by utilizing material substitutions, part modifications, processing and fabrication differences and use of alternative parts currently in production and used on other vehicles and applications.

**Table 4.6-6: Summary of Mass Reduction Concepts Initially Considered for the Rear Suspension Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Rear Suspension Subsystem** | | | |
| Leaf Spring | Make out of high strength steel | 5-10% wt save | 10-15% cost increase |
| | Make out of composite epoxy resin (reinf w/cont-glass-fiber filaments) | ~3x lighter | 60-75% cost increase |
| | Replace from 2012 GMC Sierra | 10-15% wt save | 10-15% cost save |
| | | | |
| Leaf Spring Bushing | Make spacer out of aluminum | 40-50% wt save | 20-30% cost increase |
| | Make bushing out of nylon | 10-15% wt save | 10-15% cost save |
| | Make tube out of aluminum | 40-50% wt save | 20-30% cost increase |
| | Eliminate tube using new bushing type | 100% wt save | 60-75% cost save |
| | Make spacer and tube out of aluminum and bushing out of nylon | 30-40% wt save | 10-20% cost increase |
| | Make spacer out of aluminum, eliminate tube and make bushing out of nylon | 50-60% wt save | 15-20% cost save |
| | | | |
| Spacer Block | Make out of forged aluminum | 40-50% wt save | 30-40% cost increase |
| | Make ut of cast aluminum | 40-50% wt save | 20-30% cost increase |
| | Make out of cast magnesium | 50-60% wt save | 50-60% cost increase |
| | Make out of plastic with inserter pin | 45-55% wt save | 50-60% cost increase |
| | Make from 2012 GMC Sierra | 2-5% wt save | 2-5% cost save |
| | | | |

**Table 4.6-6 continued next page**

**Table 4.6-6 (Cont'd)**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Rear Suspension Subsystem Continued** | | | |
| Saddle Bracket | Make out of high strength steel | 5-10% wt save | 5-10% cost save |
| | Make out of stamped aluminum | 50-60% wt save | 40-50% cost increase |
| | Make out of cast magnesium | 60-70% wt save | 50-60% cost increase |
| | Make out of plastic | 50-60% wt save | 45-55% cost increase |
| | | | |
| Shackle Bracket | Make out of high strength steel | 5-10% wt save | 5-10% cost save |
| | Make out of welded fab titanium | 20-30% wt save | 7-8x cost increase |
| | Make out of welded fab aluminum | 45-55% wt save | 70-80% cost increase |
| | Investigate lighter shackle in A2MAC1 database | Silverado has the lowest mass shackle bracket compared with other vehicles in the same weight class | |
| | | | |
| Shackle Bracket Bushing | Make spacer out of aluminum | 40-50% wt save | 25-35% cost increase |
| | Make bushing out of nylon | 10-15% wt save | 10-15% cost save |
| | Make spacer out of aluminum & bushing out of nylon | 45-55% wt save | 10-15% cost increase |
| | | | |

### 4.6.2.5 Selection of Mass Reduction Ideas

**Table 4.6-7** shows a subset of the ideas generated for the Rear Suspension Subsystem that were selected for detailed evaluation of both mass savings achieved and manufacturing cost. Also included are part substitutions from other vehicle designs, such as those in use in the 2012 GMC Sierra.

**Table 4.6-7: Mass Reduction Ideas Selected for the Detailed Rear Suspension Subsystem Analysis**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|---|---|---|
| **04** | **02** | **00** | **Rear Suspension Subsystem** | |
| 04 | 02 | 00 | Leaf Spring | Normalize & make out glass filled reinforced plastic |
| | | | | |
| 04 | 02 | 00 | Leaf Spring Bushing (2.75") | Eliminate tube, make spacer out of aluminum and bushing out of Nylon |
| | | | | |
| 04 | 02 | 00 | Leaf Spring Bushing (2.50") | Eliminate tube, make spacer out of aluminum and bushing out of Nylon |
| | | | | |
| 04 | 02 | 00 | Spacer Block | Make out of cast magnesium |
| | | | | |
| 04 | 02 | 00 | Saddle Bracket | Make out of cast magnesium |
| | | | | |
| 04 | 02 | 00 | Shackle | Make out of stamped aluminum |
| | | | | |
| 04 | 02 | 00 | Shackle Bushing | Make spacer out of aluminum and bushing out of Nylon |

The new mass reduced Rear Suspension System (**Image 4.6-41**) configuration is still that of typical vehicle designs utilized by nearly all OEMs. The reductions in mass achieved were accomplished by improving and replacing individual sub-assemblies and components. The overall design and function remains the same thus eliminating drastic revisions causing significant vehicle interface redesigns.

**Image 4.6-41: Rear Suspension Rotor Mass Reduced System Application Example**
*(Source: http://i108.photobucket.com/albums/n21/raymederos/DSCN1633.jpg)*

### 4.6.2.5.1 Leaf Spring Assembly

The solution chosen to be implemented on the rear leaf spring assembly (**Image 4.6-42**) was the normalization of size from a 2012 GMC Sierra leaf spring assembly and then to make it of glass fiber reinforced plastic. The baseline design uses three leafs while the redesigned leaf spring assembly will require only two. The total mass of this replacement assembly is now 10.5 kg versus the baseline assembly mass of 26.2 kg.

**Image 4.6-42: Rear Leaf Spring Mass Reduced Assembly**
*(Source:http://www.bing.com/images/search?q=Fiberglass+Leaf+Spring+Lightweight&FORM)*

#### 4.6.2.5.2 Front and Rear Leaf Spring Bushing Assembly

The new leaf spring bushing assembly (**Image 4.6-43**) is still a multi-piece assembly, with the isolator portion made from nylon instead of rubber. The inner sleeve is now an aluminum rolled tube and the outer sleeve is eliminated. The front bushing assembly has a new mass of 0.191 kg compared to the baseline mass of 0.439 kg while the rear bushing assembly has a new mass of 0.133 kg versus the baseline mass of 0.342 kg.

**Image 4.6-43: Front and Rear Leaf Spring Bushing Assembly**
*(Source: www.kseriesparts.com/merchant.mvc)*

#### 4.6.2.5.3 Lower U Bolt Spacer Block

The mass-reduced lower U-bolt spacer block (**Image 4.6-44**) is now made out of cast magnesium. An additional 55% material volume was added in order to increase the blocks strength relative to cast iron.

This new spacer has a mass of 0.568 kg compared to the baseline mass of 1.51 kg. (As with all suspension components, proper validation must be performed based on the vehicle performance requirements.)

**Image 4.6-44: Lower U Bolt Spacer Block Mass Reduced Component Example**
*(Source: http://www.rubiconexpress.com/images/truck-and-jeep/parts/.jpg)*

4.6.2.5.4 Saddle Bracket

The new saddle bracket (**Image 4.6-45**) is now made out of die casted magnesium. Due to the replacement of steel with aluminum, an additional 40% material volume was required. The saddle bracket now has a new mass of 0.491 kg versus the baseline mass of 1.30 kg.

**Image 4.6-45: Saddle Bracket Mass Reduced Component Example**
*(Source: http://www.indiamart.com/svtechno-castings/steel-castings.html)*

#### 4.6.2.5.5 Shackle Bracket Assembly

The solutions chosen to be implemented on the shackle bracket assembly, (**Image 4.6-46**) was to make the shackle bracket from stamped aluminum, the bushing out of nylon, and the bushing spacer out of rolled aluminum. This allowed for both an assembly mass and cost reduction. The total mass of this replacement assembly is 0.444 kg versus the baseline assembly mass of 0.845 kg.

**Image 4.6-46: Shackle Bracket Mass Reduced Assembly**
*(Source: http://www.bing.com/images/search)*

#### 4.6.2.5.6 Shackle Bracket

The new shackle bracket (**Image 4.6-47**) is made from stamped aluminum. Due to the replacement of steel with aluminum, an additional material volume of 40% was required. Due to loading and strength performance requirements, proper validation testing would be required dependent on the application. The new shackle bracket has a new mass of 0.317 kg compared to the baseline bracket mass of 0.648 kg.

**Image 4.6-47: Shackle Bracket**
*(Source: http://thesuspensionking.com/catalog/index.)*

### 4.6.2.5.7 Shackle Bracket Bushing Assembly

The redesigned shackle bracket bushing assembly (**Image 4.6-48**) is still of standard design but utilizes an alternate material of nylon versus rubber for the bushing and the inner sleeve is now rolled aluminum tube instead of steel. The bushing mass stays the same at 0.059 kg while the spacer has a new mass of 0.068 kg compared to the baseline mass of 0.138 kg.

Many aftermarket as well as OEM manufacturers now utilize this new bushing material choice for many vehicle applications. This is due to improved handling performance, increased component life, and in some cases a small amount of mass reduction.

**Image 4.6-48: Shackle Bracket Bushing Mass Reduced Assembly Example**
*(Source: http://www.cdxetextbook.com/steersusp/susp/layouts/bushes.html)*

#### 4.6.2.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.6-8** shows the results of the mass reduction ideas that were evaluated for the Rear Suspension Subsystem. This resulted in a subsystem overall mass savings of 35.7 kg and a cost penalty differential of $113.47.

**Table 4.6-8: Mass Reduction and Cost Impact for the Rear Suspension Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Ideas | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys/ Sub-Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 04 | 02 | 00 | Rear Suspension | | | | | | |
| 04 | 02 | 01 | Rear Road Springs | D | 35.7 | -$113.47 | -$3.17 | 56.3% | 1.46% |
| | | | | D | 35.7 (Decrease) | -$113.47 (Increase) | -$3.17 (Increase) | 56.3% | 1.46% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.6.3 Shock Absorber Subsystem

#### 4.6.3.1 Subsystem Content Overview

**Image 4.6-49** is a picture of the front strut assembly within the Shock Absorber Subsystem. The strut assembly includes the strut sub-assembly, jounce bumper, coil, upper and lower insulators, spring seat, upper strut mount, and associated hardware and fasteners.

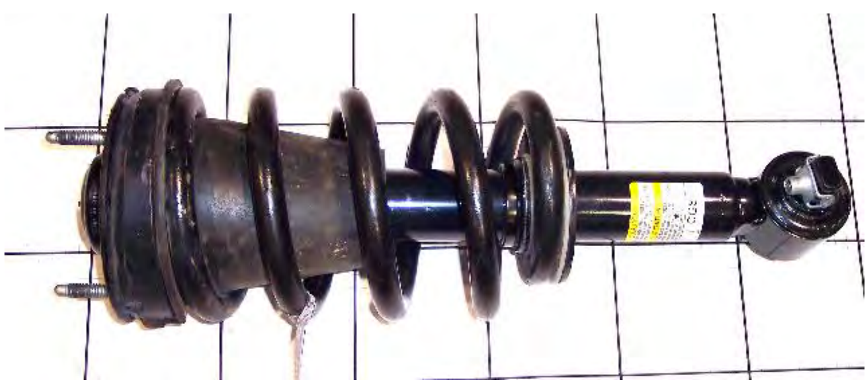


**Image 4.6-49: Front Shock Absorber Subsystem Current Sub-Assembly Components**
*(Source: FEV, Inc.)*

As seen in **Image 4.6-50**, the Front Strut Damper Subsystem consists of the strut sub-assembly, jounce bumper, coil, upper and lower insulators, spring seat, upper strut mount, and associated hardware and fasteners.

**Image 4.6-50: Front Strut / Damper Subsystem Current Major Components**
*(Source: FEV, Inc.)*

**Table 4.6-9** shows that the Shock Absorber Subsystem consists of the front strut/damper assembly and the rear strut/damper assembly. The most significant contributor to the mass of the Shock Absorber Subsystem is the front strut/damper assembly (approximately 79.9%) is followed by the rear strut/damper assembly (approximately 20.1%).

**Table 4.6-9: Mass Breakdown by Sub-subsystem for the Shock Absorber Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 04 | 03 | 00 | **Shock Absorber Subsystem** | |
| 04 | 03 | 01 | Front Strut / Damper Asm | 19.5 |
| 04 | 03 | 02 | Rear Strut / Damper Asm | 4.89 |
| | | | | |
| | | | **Total Subsystem Mass =** | **24.4** |
| | | | **Total System Mass =** | **301.2** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **8.1%** |
| | | | **System Mass Contribution Relative to Vehicle =** | **0.99%** |

### 4.6.3.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado Front Strut/Damper Subsystems (**Image 4.6-51**) represent typical industry standards. This includes a focus on functional performance and durability with least material cost. Chevrolet also focuses on providing similar if not identical components across all platform variants to take advantage of economies of scale in minimizing production and purchasing costs.

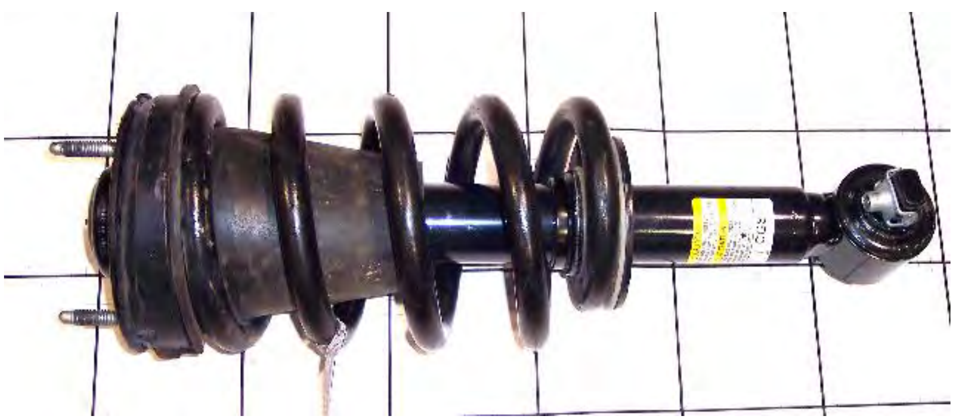


**Image 4.6-51: Front Strut Module Assembly Subsystem Current Configuration Example**
*(Source: FEV, Inc.)*

### 4.6.3.2.1 Strut / Damper Module Assemblies

The baseline OEM Chevrolet Silverado front strut/damper module assemblies is a multi-piece design of stamped steel fabrications welded into sub-assemblies along with various molded and sub-assembled components that are then filled with fluid and charged to pressure. The only components that were investigated for changes are the front strut coil spring (**Image 4.6-52**) and the mounting rod assembly (**Image 4.6-53**). The front strut assemblies have a combined total mass of 19.5 kg.

Many high-performance and luxury models such as BMW, Mercedes, Audi, and even some GM vehicles utilize alternate materials and designs in order to improve mass and expense across many of these components within these assemblies. These individual components are reviewed and shown individually here in greater detail.

#### *4.6.3.2.1.1 Front Strut Coil Springs*

The baseline OEM Chevrolet Silverado front strut coil springs (**Image 4.6-52**) are single-piece, steel hot-wound coil springs. This component has a mass of 5.53 kg for the front springs. Some vehicle models and manufacturers have begun utilizing alternate materials and design changes for springs including HSS and other steel alloy variations. Other materials, including long fiber polymers, have successfully been implemented for leaf spring applications as well as coil spring applications on small passenger cars.

**Image 4.6-52: Front Strut Coil Spring Current Component Example**
*(Source: FEV, Inc.)*

#### *4.6.3.2.1.2 Front Strut Mounting Shaft Assembly*

The baseline OEM Chevrolet Silverado front strut mounting shaft assembly is a single-piece steel design and has a mass of 1.16 kg. Mounting shafts (**Image 4.6-53**) have normally been made from forged steel for adequate strength and function. Now, with advances in materials and processing methods, other choices are available and being utilized in aftermarket and high-performance applications as well as OEM vehicle markets. Among some of these alternate mediums are aluminum, titanium, steel, and magnesium. Forming and fabrication methods include casting, forging, and billet machining.


**Image 4.6-53: Front Strut Mounting Shaft Current Assembly Example**
*(Source: FEV, Inc.)*

### 4.6.3.3 Mass Reduction Industry Trends

Basic trends in shock absorber technology include low mass materials where function is not deteriorated. Also, high strength steel is used for mass reduction of springs, notably in Alfa Romeo and BMW vehicles.

Audi has recently announced their decision to launch the new A6 Avant Ultra using Composite (Glass Fiber Reinforced Plastic) coil springs (**Image 4.6-54**). The composite coil springs will weigh approximately 4 kg lighter than the traditional steel springs.

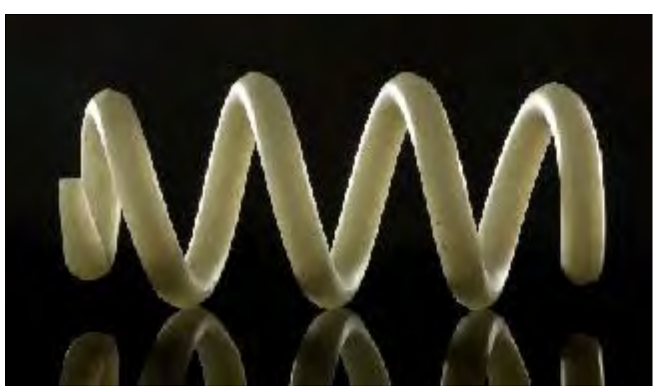


**Image 4.6-54: First Composite Material Coil Springs glass fiber reinforced polymer (GFRP)**
*(Source: http://articles.sae.org/13642/)*

Another trend in shock absorber technology is integrating more and more electronics. Electronic dampers allow a large range between maximum and minimum damping levels and adjust instantly to ensure ride comfort and firm vehicle control. By integrating mechanical and electronic functions within the shock absorber system, automakers can improve handling and potentially reduce costs as technologies mature.

Delphi has developed the MagneRide™ concept (**Image 4.6-55**), in which a Magneto-Rheological (MR) fluid passes through an orifice that can be "restricted" by applying an electric field. The MagneRide system produces a mechanically simple but very responsive and controllable damping action without any valves. Synthetic hydraulic oil contains suspended iron particles. When surrounded by a magnetic field, these particles realign, changing the viscosity of the fluid.

These MR shocks and struts feature a tube which rides on a stationary internal piston containing an electromagnet. When current is fed to the magnet, the surrounding MR fluid instantaneously changes viscosity to resist the tube/piston movement in a way that best copes with road conditions. According to Delphi, the fluid transforms within a millisecond from the consistency of mineral oil (to compensate for low dampening forces) to a thin jelly consistency for high dampening.

Since the viscosity of the MR fluid can be infinitely varied through changes in the current, Delphi shocks and struts are designed to provide a far greater dampening range compared with conventional shocks. This translates into a smoother and more responsive ride. As the tube is the only moving part, the shock is more trouble-free and should not wear out as quickly as conventional shocks. As for other advantages, Delphi says its new technology reduces suspension weight and overall costs.

**Image 4.6-55: Delphi MagneRide™ Strut System**
*(Source: http://www.search-autoparts.com/searchautoparts/article/articleDetail.jsp?id=68222)*

#### 4.6.3.4 Summary of Mass Reduction Concepts Considered

The brainstorming activities generated the ideas shown below for the Front Strut/Shock Absorber/Damper Sub-subsystems (**Table 4.6-10**). The majority of these mass reduction ideas are related to technologies in production on other vehicles and alternatives to steel. This includes part modifications, material substitutions, and use of parts currently in production on other vehicles.

**Table 4.6-10: Summary of Mass Reduction Concepts Initially Considered for the Front Strut/Shock/Damper Sub-Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Shock Absorber Subsystem** | | | |
| Spring | Make out of titanium alloy (Timetal LCB) | 20-30% wt save | 5-6x cost increase |
| | Make out of high strength steel | 5-10% wt save | 10-20% cost save |
| | Make from Mubea spring winding process | 20-30% wt save | 20-30% cost save |
| | Replace from 2012 Dodge Durango | 30-40% wt save | 30-40% cost save |
| | | | |
| Lower Strut Mounting Assembly | Make out of forged aluminum | 40-50% wt save | 20-30% cost increase |
| | Make bushing out of nylon | 10-15% wt save | 10-20% cost save |
| | Make rod out of aluminum & bushing out of nylon | 30-40% wt save | 5-10% cost increase |

#### 4.6.3.5 Selection of Mass Reduction Ideas

**Table 4.6-11** shows the subsets of the ideas generated from the brainstorming activities listed in the previous chart for the Front Strut/Shock Absorber/Damper Sub-subsystem.

**Table 4.6-11: Mass Reduction Ideas Selected for the Shock Absorber Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|---|---|---|
| **04** | **03** | **00** | **Shock Absorber Subsystem** | |
| 04 | 03 | 00 | Spring | Make from Mubea's spring winding process and material |
| | | | | |
| 04 | 03 | 00 | Front Strut Lower Mount | Make mounting rod out of forged aluminum and bushing out of Nylon |

The solution for the mass reduced Shock Absorber Subsystem is illustrated in **Image 4.6-56**. The changes made at the individual component and sub-assembly levels are explained in greater detail following the image.

**Image 4.6-56: Front Strut / Damper Assembly Mass Reduced Configuration Example**
*(Source: http://www.classicperform.com/NewProducts/QAShocks/Shock1.jpg)*

### 4.6.3.5.1 Front Strut Mounting Assembly

The solutions selected to be implemented on the front strut/damper assembly (**Image 4.6-49**) span different components and sub-assemblies. Although the overall design and function of the strut modules remain the same, changes were instituted across the spring and the lower mounting mechanism. The affected designs are detailed in the following sections for each area of redesign and change. The primary sub-assemblies and components that were investigated for implemented changes are the front strut coil spring and the lower mount assembly (**Image 4.6-58**). The new mass-reduced front strut assembly has a mass of 6.51 kg versus the baseline mass of 9.73 kg.

#### *4.6.3.5.1.1 Front Strut Coil Spring*

The selected solution for the front strut coil springs (**Image 4.6-57**) is to form the coil springs using Mubea's primary steel material and winding process.

The springs are produced using wire rod that is drawn and inductively hardened to tensile strengths of up to 2,100Mpa. Due to the replacement of steel with Mubea's high strength steel, these new springs have an individual mass of 2.73 kg compared to the baseline spring of 5.53 kg.

**Image 4.6-57: Front Strut Coil Spring Mass Reduced Component Example**
*(Source: http://www.mubea.com/products-technologies/automotive/suspension/suspension-coil-springs/)*

#### *4.6.3.5.1.2 Front Lower Strut Mounting Assembly*

The changes made on the front lower strut mounting assembly (**Image 4.6-58**) are to use forged aluminum instead of steel for the shaft and change the rubber isolator to nylon. Due to this replacement of steel to aluminum, an additional material volume of 40% was required. Mounting shafts have normally been made from various grades of steel for adequate strength. Now with advances in materials and processing methods other choices are available and being utilized in aftermarket and high-performance applications as well as some OEM vehicle markets. Among some of these alternate are aluminum and titanium. Forming and fabrication methods include forging and billet machining. The bushings are still of standard design but utilize an alternate material of nylon instead of rubber. The bushings have an individual mass of 0.398 kg versus 0.464 kg for the baseline bushings and the shafts have an individual mass of 0.341 kg versus the baseline mass of 0.697 kg.

Many aftermarket and OEM manufacturers now use this new material choice for many vehicle applications. This is due to improved handling performance, increase component life, and even a small amount of mass reduction.

**Image 4.6-58: Front Strut Mounting Mass Reduced Assembly Example**
*(Source: http://www.track-star.net/store/corvette-c6-z06-suspension/)*

### 4.6.3.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.6-12** shows the results of the mass reduction ideas that were evaluated for the Shock Absorber Sub-subsystem. This resulted in a subsystem overall mass savings of 6.4 kg and a cost increase differential of $3.77.

**Table 4.6-12: Mass Reduction and Cost Impact for the Shock Absorber Subsystem (Front Strut/Damper Assembly Sub-Subsystem)**

| | | | | Net Value of Mass Reduction Ideas | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys/ Sub-Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 04 | 03 | 00 | Shock Absorber Subsystem | | | | | | |
| 04 | 03 | 01 | Front Strut / Damper Asm | B | 6.44 | -$3.77 | -$0.58 | 26.5% | 0.26% |
| | | | | B | 6.44 (Decrease) | -$3.77 (Increase) | -$0.58 (Increase) | 26.5% | 0.26% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.6.4 Wheels and Tires Subsystem

#### 4.6.4.1 Subsystem Content Overview

**Image 4.6-59** shows the relative location of the road wheel and tire sub-assemblies and the spare wheel and tire sub-assembly on the vehicle chassis.

**Image 4.6-59: Road Wheel and Tire Position Diagram**
*(Source: http://image.trucktrend.com/f/31572814+w750+st0/2011-chevrolet-silverado-HD-frame.jpg)*

The following images represent the major sub-assemblies and components in the Wheels and Tires Subsystem. These include the road wheel and tire assembly (**Image 4.6-60**) and the spare wheel and tire assembly (**Image 4.6-63**). The current OEM Chevrolet Silverado Wheels and Tires Subsystem have a total mass of 158.6 kg.

In **Table 4.6-13**, the Wheels and Tires Subsystem consists of the Road Wheels and Tire Assembly Sub-subsystem and the Spare Wheel and Tire Assembly Sub-subsystem. The most significant contributors to the mass of this subsystem are the Road Wheels and Tire Assembly Sub-subsystem (approximately 75.4%) followed by the Spare Wheel and Tire Assembly Sub-subsystem (approximately 24.6%).

**Table 4.6-13: Mass Breakdown by Sub-subsystem for the Wheels and Tires Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 04 | 04 | 00 | **Wheels And Tires Subsystem** | |
| 04 | 04 | 01 | Road Wheels and Tire Assembly | 119.6 |
| 04 | 04 | 02 | Spare Wheel and Tire Assembly | 39.0 |
| | | | | |
| | | | **Total Subsystem Mass =** | **158.6** |
| | | | **Total System Mass =** | **301.2** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **52.7%** |
| | | | **System Mass Contribution Relative to Vehicle =** | **6.46%** |

### 4.6.4.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado Wheels and Tires Subsystem represent typical industry standards. This includes a focus on style, functional performance and durability with least material cost. Chevrolet also focuses on providing similar, if not identical, components across all platform variants to take advantage of economies of scale in minimizing production and purchasing costs.

#### 4.6.4.2.1 Road Wheel and Tire Assemblies

The Silverado uses four standard road wheel and tire assemblies (**Image 4.6-60**) with radial molded tires mounted on an aluminum rims. The current OEM Silverado Road Tire Assembly Sub-subsystem has a total mass of 119.4 kg.

**Image 4.6-60: Road Wheel and Tire Current Assembly**
*(Source: FEV, Inc.)*

#### 4.6.4.2.2 Road Wheels

The Chevrolet Silverado OEM road wheels (**Image 4.6-61**) are single-piece, cast aluminum design. The size of OEM wheel used on the Silverado is an 18-inch outer diameter by 8-inch wide. Although alternate materials (magnesium, GF polymers, and carbon fiber) exist and are used by some aftermarket manufacturers, they are uncommon and very ineffective for cost in most applications. The current Silverado road wheels, four wheels, have a total mass of 48.5 kg.


**Image 4.6-61: Road Wheel Current Component**
*(Source: http://www.originalwheels.com/chevrolet-wheels/silverado2011rims.php)*

#### 4.6.4.2.3 Road Tires Sub-Assembly

The Chevrolet Silverado OEM road tires are multi-layer design of various materials all over-molded NR. The size of the OEM tire used on the Chevrolet Silverado is P265/65R18. Alternate material variations are used for the internal layers as well as the final over-molding compound. But manufacturers use these variables to help tune a specific tire design to the performance desired for a particular vehicle application. **Image 4.6-62** shows a common tire design and the features and the naming nomenclature associated with it. No significant material developments exist that allow any appreciable weight savings while maintaining a standard design configuration. The current Silverado road tires, four tires, have a total mass of 69.5 kg.

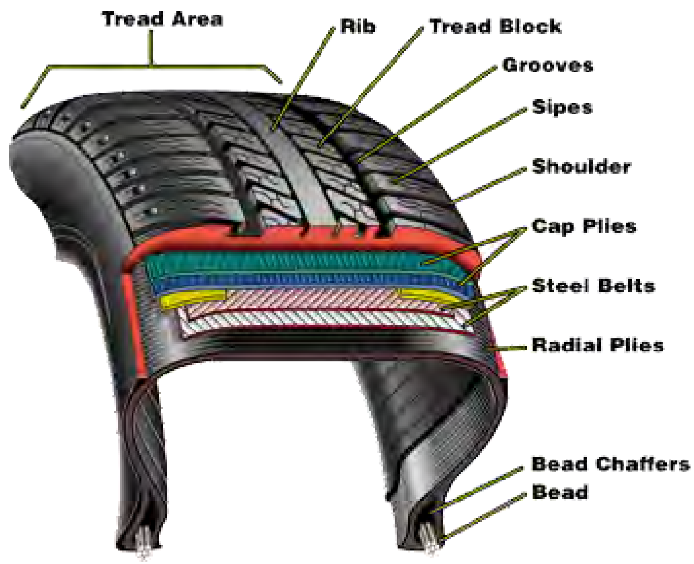



**Image 4.6-62: Road Wheel Current Component Design Example**

*(Source: http://www.vbattorneys.com/practice_areas/defective-product-lawyer-product-liability-attorney-houston-texas.cfm)*

#### 4.6.4.2.4 Spare Wheel and Tire Assembly

The spare wheel and tire assembly (**Image 4.6-63**) is a typical narrow (and short side-walled) molded spare tire mounted on a large diameter, stamped steel wheel assembly. The current OEM Chevrolet Silverado Spare Tire Assembly Sub-subsystem has a mass of 39.0 kg.

**Image 4.6-63: Spare Wheel and Tire Current Assembly Example**
*(Source: http://www.ebay.com/itm/2007-2011-Silverado-Sierra-1500-GM-SUV-Spare)*

#### *4.6.4.2.4.1 Spare Wheel*

The Chevrolet Silverado OEM Spare Wheel (**Image 4.6-64**) has a large diameter and narrow, stamped steel fabrications. Although alternate materials (aluminum, magnesium, GF polymers, and carbon fiber) exist, they are not typically used for spare wheels due to lack of mass versus cost reduction. Therefore, they are not used by any manufacturer, although they could. The current OEM Silverado spare wheel has a 14.5 kg mass.

**Image 4.6-64: Spare Wheel Current Component Example**
*(Source: FEV, Inc.)*

#### *4.6.4.2.4.2 Spare Tire Sub-Assembly*

The Chevrolet Silverado OEM spare tire (**Image 4.6-65**) is multiple layers of steel and plastic, over-molded by NR. Alternate material variations are used for the internal and external layers, but manufacturers use these variables to help tune a specific tire design to the desired performance. The current OEM Chevrolet Silverado spare tire has a mass of 17.0 kg.

**Image 4.6-65: Road Wheel Current Component Example**
*(Source: FEV, Inc.)*

#### 4.6.4.2.5 Lug Nuts

The lug nuts, or wheel fastener nuts (**Image 4.6-66**), are a typical cold-headed steel configuration with a stamped steel, chrome-plated shell pressed over the nut surface. The current OEM Chevrolet Silverado lug nuts (24 pieces) have individual mass of 0.042 kg.

**Image 4.6-66: Lug Nut Current Components**
*(Source: FEV, Inc.)*

#### 4.6.4.3 Mass Reduction Industry Trends

The ICCT Lotus Engineering report of March 2010 (*"An Assessment of Mass Reduction Opportunities for a 2017-2020 Model Year Program"*) describes several industry examples including Alcoa aluminum forged wheels, carbon fiber composites, two-piece low-mass wheels, Michelin Tweel, and Active Wheel designs.

New proprietary magnesium alloys are being developed for racing applications, including wheels and lug nuts, with claims of matching the strength of steel with impressive mass reduction.

As mentioned in **Section 4.6.1.3**, basalt fiber is a potential low cost substitute for carbon fiber when production capabilities can support automotive quantities.

Tire technology has also seen advancement in recent years: Goodyear's Air Maintenance Technology (AMT) system automatically keeps tires inflated to the optimum pressure without any human intervention. An internally mounted valve detects a low-pressure condition and then automatically opens up to allow airflow into the tire as it rolls down the road.

Ecopia tires, from Bridgestone (as seen on the Nissan Leaf), improves rolling resistance by 36%, which equates to a 4% fuel economy improvement.

Bridgestone also recently announced the development of its "Large and Narrow Concept Tire." This technology helps achieve improved fuel economy which reduces $CO_2$ emissions. Additionally, the air pressure is greater than conventional tires, the tread design incorporates new pattern styles, and new materials are designed specifically for use in these tires. Consequently, this tire design allows for a significantly lower rolling resistance yet higher road grip performance.

Yokohama has a patented process that infuses the tire tread rubbers with the natural oil from orange peels. Yokohama calls this petroleum-reduced compound Super Nano-Power Rubber™ (SNPR), claiming it improves tread life and reduces rolling resistance. This technology was initially utilized in Yokohama's dB Super E-spec™ tire.

Cooper Tire states in its report titled "Improving Vehicle Fuel Efficiency through Tire Design, Materials, and Reduced Weight" that it has been working with the National Renewable Energy Laboratory to develop a new class of tires that improves fuel efficiency by a minimum of 3% and reduces overall tire weight by 20%. The report says the strategy is to "evaluate partial replacement (levels) of carbon black and silica with nano-fiber reinforcement in tire component compounds for optimum performance/cost opportunities."

#### 4.6.4.4 Summary of Mass Reduction Concepts Considered

The brainstorming activities for Wheels and Tires Subsystem generated the ideas shown in **Table 4.6-14**. The majority of these mass reduction ideas are related to technologies in production on other vehicles and size alternatives. There are also ideas that cover part design modifications as well as material substitutions.

**Table 4.6-14: Summary of Mass Reduction Concepts Initially Considered for the Wheels and Tires Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Wheels And Tires Subsystem** | | | |
| All Tires (P225/60R19) | Replace from 2012 GMC Sierra | 10-20% wt save | 10-15% cost save |
| All Wheels (19 x 7.5) | Ultra-lt wt forged aluminum wheels | 15-20% wt save | 10-15% cost increase |
| | Lt wt wheels (hybrid glass & carbon fiber composite) | 40-50% wt save | 1-2x cost increase |
| | Replace from 2006 Dodge Ram | 1-5% wt save | 1-5% cost save |
| Lug Nuts | Make out of aluminum | 40-50% wt save | 10-20% cost increase |
| | Make out of titanium | 20-30% wt save | 4-5x cost increase |
| Spare Tire & Wheel | Add lightening holes in spare wheel | 1-5x wt save | 1-5% cost save |
| | Make spare wheel out of aluminum | 40-50% wt save | 45-55% cost increase |
| | Lt wt wheels (hybrid glass & carbon fiber composite) | 4-5x wt save | 2-3x cost increase |
| | Replace wheel from 2006 Dodge Ram | 4-5x wt save | 2-3x cost increase |
| | Replace tire from 2006 Dodge Ram | 1-5x wt save | 1-5% cost save |
| | Eliminate spare tire & spare tire hold down | 100% wt save | 100% cost save |

#### 4.6.4.5 Selection of Mass Reduction Ideas

**Table 4.6-15** shows the mass reduction ideas for the major components of the Wheels and Tires Subsystem that were chosen for detailed evaluation. There are five components outlined that are being redesigned and changed in order to achieve mass reductions.

**Table 4.6-15: Mass Reduction Ideas Selected for the Detailed Wheels and Tires Subsystem Analysis**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|---|---|---|
| **04** | **04** | **00** | **Wheels & Tires Subsystem** | |
| 04 | 04 | 00 | All Tires (P225/60R19) | Normalize to 2007 Ford F150 |
| | | | | |
| 04 | 04 | 00 | All Wheels (19 x 7.5) | Make out of ultra-lt wt forged al wheels (cross-spoked) |
| | | | | |
| 04 | 04 | 00 | Lug Nuts | Make lug nuts out of aluminum |
| | | | | |
| 04 | 04 | 00 | Spare Tire Wheel | Make spare tire wheel out of aluminum |
| | | | | |
| 04 | 04 | 00 | Spare Tire | Normalize to 2006 Dodge Ram |

The mass-saving solutions selected for the various components within the Wheel and Tire Subsystem are primarily by component substitution from the 2007 Ford F150 and the 2006 Dodge Ram, as well as material substitution and manufacturing processes. The details of these changes vary greatly and are summarized in greater detail in the following sections.

#### 4.6.4.5.1 Road Wheel and Tire Assemblies

The solution selected for the road wheel and tire assemblies (**Image 4.6-67**) is to substitute the current OEM tires with those from the 2007 Ford F150 and make material substitutions for the road wheels. This would change the effective mass without altering the effective design content or visual aspect in relation to the vehicle appearance. Both vehicles have aluminum cast rims and similar tire profiles. The new implemented road wheel and tire assemblies, four pieces, have a total mass of 106.3 kg versus the baseline total mass of 118.0 kg.

**Image 4.6-67: Road Wheel and Tire Mass-Reduced Assembly**
*(Source: http://www.sgmerc.com/topic/8751-show-us-your-bbk-rims/page-6)*

### *4.6.4.5.1.1 Road Wheels*

The chosen mass reduction for the road wheels (**Image 4.6-68**) is to use an ultra-light weight forged aluminum (cross-spoked) wheel design. This new road wheel, four pieces, has a total mass of 42.4 kg versus the baseline total mass of 48.5 kg.

**Image 4.6-68: Road Wheel Mass-Reduced Component**
*(Source: http://www.auto-technik.com.sg/index.aspx?MenuID=36)*

#### *4.6.4.5.1.2 Road Tire*

The solution selected for the road tire assemblies (**Image 4.6-69**) is a substitution of using the 2007 Ford F150 as a replacement. The size of the tire used on the 2007 F150 is P265/60R18. This size was normalized up to a P265/65R18 in order to maintain the appearance and handling function of the current Silverado. The new road tire assemblies, four pieces, have a total net mass of 63.9 kg compared to the total baseline mass of 69.5 kg.


**Image 4.6-69: Road Wheel Mass-Reduced Assembly**
*(Source: http://a2mac1.com)*

#### 4.6.4.5.2 Spare Wheel and Tire Assembly

The chosen solutions being implemented for the spare wheel and tire assembly (**Image 4.6-70**) is to substitute a 2006 Dodge Ram tire and replace the steel wheel with an aluminum wheel. The design configuration and construction is the same and will not affect function or performance. The mass-reduced spare wheel and tire assembly has a mass of 24.1 kg versus the total baseline mass of 31.5 kg.

**Image 4.6-70: Spare Wheel and Tire Mass-Reduced Assembly**
*(Source: http://www.ebay.com/)*

### *4.6.4.5.2.1 Spare Wheel*

The new redesigned spare wheel (**Image 4.6-71**) is a cast aluminum wheel. The new mass reduced spare wheel has a mass of 9.24 kg versus the baseline mass of 14.5 kg.

**Image 4.6-71: Spare Wheel Mass-Reduced Assembly**
*(Source: http://www.autopartswarehouse.com/shop_parts/wheel/gmc.html)*

#### *4.6.4.5.2.2 Spare Tire*

The mass reduced spare tire assembly (**Image 4.6-72**) was achieved by replacing the Silverado tire with the 2006 Dodge Ram tire. This resulted in a new mass of 14.9 kg versus the baseline mass of 17.0 kg.

**Image 4.6-72: Road Wheel Mass-Reduced Component**
*(Source:http://a2mac1.com/Autoreverse/reversepart.asp?productid=103&clientid=1&producttype=2)*

#### 4.6.4.5.3 Lug Nuts

The lug nuts (**Image 4.6-73**) were standard steel configuration, as true with most OEMs. The new solution implemented for these fasteners was to use aluminum material with a conical interface design. Due to the replacement of steel with aluminum, an additional material volume of 50% was required. This style of lug is commonly used by aftermarket manufacturers due to tremendous weight savings and reduction to unsprung rotational mass. The new lug nuts (24 pieces) are calculated to have a total new mass of 0.504 kg compared to the total baseline mass of 1.01 kg.

**Image 4.6-73: Lug Nut Mass-Reduced Component Examples**
*(Source: http://www.rjracecars.com/Aluminum-Lug-Nuts-5818-Black-Prodview.html)*

#### 4.6.4.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.6-16** shows the results of the mass reduction ideas that were evaluated for the Wheels and Tires Subsystem. The implemented solutions resulted in a subsystem overall mass savings of 19.6 kg and a cost increase of $119.89.

**Table 4.6-16: Mass Reduction and Cost Impact for the Wheels and Tires Subsystem**

| | | | | Net Value of Mass Reduction Ideas | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys/ Sub-Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 04 | 04 | 00 | Wheels And Tires Subsystem | | | | | | |
| 04 | 04 | 01 | Road Wheels and Tire Assembly | X | 12.2 | -$96.89 | -$7.96 | 7.7% | 0.50% |
| 04 | 04 | 02 | Spare Wheel and Tire Assembly | D | 7.39 | -$23.00 | -$3.11 | 4.7% | 0.30% |
| | | | | X | 19.6 (Decrease) | -$119.89 (Decrease) | -$6.13 (Decrease) | 12.3% | 0.80% |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.6.5 Secondary Mass Reduction / Compounding

#### 4.6.5.1 Subsystem Content Overview

The intent of investigating secondary mass savings is to quantify how much suspension mass could be further reduced by reducing the vehicle mass.

To calculate the allowable secondary mass reduction (**Table 4.6-17**), the Chevrolet Silverado curb weight was added to the tongue and payload weights to obtain a baseline result. Next, the curb weight was reduced by 20% and added to the tongue and payload weights to obtain a mass reduction result. The mass reduction and baseline results were ratioed to obtain the allowable mass reduction factor of 12.7%.

**Table 4.6-17: Allowable Secondary Mass Reduction Calculation**

| Chevrolet Silverado Suspension System<br>Secondary Mass Reduction/Compounding Calculation | |
|---|---|
| Chevrolet Silverado Tongue Weight (kgs) | 499 |
| Chevrolet Silverado Payload Weight (kgs) | 873 |
| Chevrolet Silverado Curb Weight (kgs) | 2454 |
| Baseline Results | 3826 |
| | |
| Chevrolet Silverado Tongue Weight (kgs) | 499 |
| Chevrolet Silverado Payload Weight (kgs) | 873 |
| Chevrolet Silverado Lightened Curb Weight (kgs) | 1963 |
| Mass Reduction (20%) Results | 3335 |
| | |
| Allowable Mass Reduction<br>(Mass Reduction Results/Baseline Results) | **12.8%** |

Suspension system components such as control arms, coil springs, leaf springs, wheels and tires are sized by vehicle mass. Secondary mass savings (**Table 4.6-18**) were derived from reduced component masses previously calculated for lightweighting technologies. All other components like those associated with the accessories and fasteners were not affected and masses were unchanged. The result is 22.4 kg of additional mass savings based on downsizing.

**Table 4.6-18: Chevrolet Silverado Suspension Compounded Mass Savings by Component**

| | Component | New Mass (kg) | Downsizing Approach | % Reduction | Compounded Mass Savings (kg) |
|---|---|---|---|---|---|
| 1 | Lower Control Arms (2) | 10.2 | Area Reduction | 12.8 | 1.31 |
| 2 | Upper Control Arms (2) | 1.52 | Area Reduction | 12.8 | 0.194 |
| 3 | Knuckle, Steering (2) | 7.46 | Area Reduction | 12.8 | 0.95 |
| 4 | Leaf Spring Asm (2) | 21 | Area Reduction | 12.8 | 2.68 |
| 5 | Coil Spring (2) | 5.46 | Area Reduction | 12.8 | 0.699 |
| 6 | Road Wheels (4) | 42 | Area Reduction | 12.8 | 5.43 |
| 7 | Road Tires (4) | 64 | Area Reduction | 12.8 | 8 |
| 8 | Spare Wheel | 9.24 | Area Reduction | 12.8 | 1.18 |
| 9 | Spare Tire | 15 | Area Reduction | 12.8 | 1.90 |
| | **Total (kg)** | **176** | | | **23** |

Material savings for compounded components was totaled to estimate the cost impact of downsizing. Labor and burden costs were considered unchanged.

**Table 4.6-19** details mass and cost impact of all lightweighting activities and compounding. These figures are based on downsizing the already lightweighted concept as outlined in previous sections. The total mass savings achieved for the Suspension System is 105.4 kg.

**Table 4.6-19: Mass Reduction and Cost Impact for Suspension System Secondary Mass Savings**

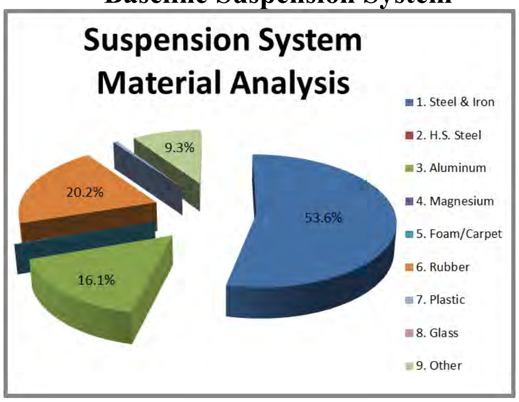
| | | | | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 04 | 00 | 00 | Suspension System | | | | | | | | |
| 04 | 01 | 00 | Front Suspension Subsystem | 21.3 | 2.44 | 23.8 | -$23.71 | $10.07 | -$13.64 | -$0.57 | 1.0% |
| 04 | 02 | 00 | Rear Suspension Subsystem | 35.7 | 2.66 | 38.4 | -$113.47 | $29.42 | -$84.06 | -$2.19 | 1.6% |
| 04 | 03 | 00 | Shock Absorber Subsystem | 6.44 | 0.694 | 7.14 | -$3.77 | $2.88 | -$0.89 | -$0.12 | 0.3% |
| 04 | 04 | 00 | Wheels And Tires Subsystem | 19.6 | 16.6 | 36.1 | -$119.89 | $63.57 | -$56.32 | -$1.56 | 1.5% |
| | | | | **83.1** (Decrease) | **22.4** (Decrease) | **105.4** (Decrease) | **-$260.84** (Increase) | **$105.94** (Decrease) | **-$154.90** (Increase) | **-$1.47** (Increase) | **4.30%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

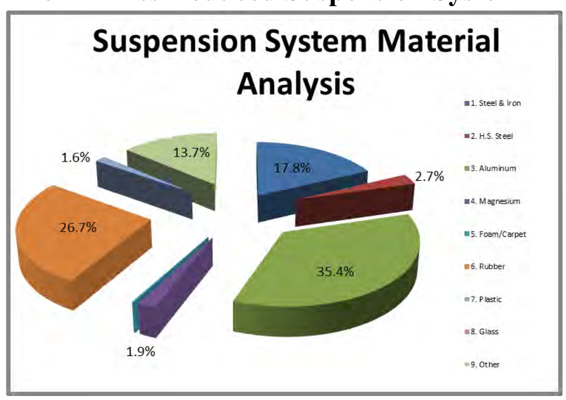
### 4.6.6 Suspension System Material Analysis

The Material Categories for the Baseline Suspension System and for the Total Mass Reduced Suspension System is shown in **Figure 4.6-3**. “Steel & Iron” was reduced from 161.5 kg (baseline mass) to 31.6 kg (total mass reduced), while aluminum increased from 48.5 kg (baseline mass) to 62.8 kg (total mass reduced). Magnesium also increased from 0.0 kg (baseline mass) to 3.45 kg (total mass reduced). Rubber decreased from 61 kg (baseline mass) to 47.4 kg (total mass reduced). Finally, the category labeled “Other” decreased from 28.1 kg (baseline mass) to 24.3 kg (total mass reduced) due to the compounding effect of the road and spare tires.

**Baseline Suspension System**




**Total Mass Reduced Suspension System**




| | | Material Categories: |
|---|---|---|
| 53.6% | 161.5 | 1. Steel & Iron |
| | 0.0 | 2. H.S. Steel |
| 16.1% | 48.5 | 3. Aluminum |
| | 0.0 | 4. Magnesium |
| 0.14% | 0.42 | 5. Foam/Carpet |
| 20.2% | 61.0 | 6. Rubber |
| 0.57% | 1.73 | 7. Plastic |
| | 0.0 | 8. Glass |
| 9.34% | 28.1 | 9. Other |
| 100% | 301.2 | TOTAL |

| | | Material Categories: |
|---|---|---|
| 17.8% | 31.6 | 1. Steel & Iron |
| 2.7% | 4.77 | 2. H.S. Steel |
| 35.4% | 62.8 | 3. Aluminum |
| 1.9% | 3.45 | 4. Magnesium |
| 0.2% | 0.422 | 5. Foam/Carpet |
| 26.7% | 47.4 | 6. Rubber |
| 1.6% | 2.77 | 7. Plastic |
| | 0.0 | 8. Glass |
| 13.7% | 24.3 | 9. Other |
| 100% | 177.5 | TOTAL |

**Figure 4.6-3: Baseline and Total Mass Reduced Suspension System Material Content**

### 4.7 Driveline System

The Driveline System is coupled to the engine/transmission assembly and is designed to deliver the energy generated by the engine, passed through the transmission to the wheels. Between the output shaft on the transmission and the rear wheels meeting the road, there is plenty of metal properly designed to handle the torque which is delivered to the wheels.

In 4-wheel drive mode the transmission provides energy to the transfer case. The output shaft of the transfer case and the front axle differential are all connected with the same type of universal/yoke/propshaft assembly as the rear axle. The front differential operates in the same manner as the rear, when engaged.

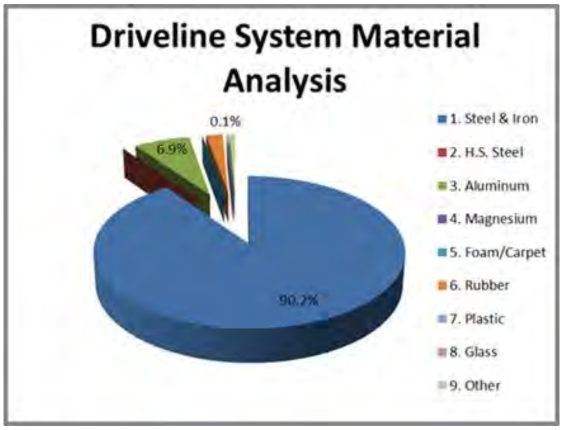
As shown in **Table 4.7-1**, the Driveline System is made up of six subsystems. The Silverado analysis and mass-reduction efforts are focused on the top four subsystems. The last two subsystems have little mass in the total system mass of this vehicle and this lack of mass does not provide any opportunities for mass-reduction.

The Silverado curb weight is 2,454 kg (5249 lbs.) with a trailer towing capacity of 4,418 kg (9720 lbs.), providing a gross vehicle weight of 6,804 kg (14969 lbs). The Driveline Subsystem has to properly support the vehicle's ability to safely and continuously move this mass.

**Table 4.7-1: Baseline Driveline System**

| System | Subsystem | Sub Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 05 | 00 | 00 | **Driveline System** | |
| 05 | 01 | 00 | Driveshaft Subsystem | 14.312 |
| 05 | 02 | 00 | Rear Drive Housed Axle Subsystem | 89.067 |
| 05 | 03 | 00 | Front Drive Housed Axle Subsystem | 52.526 |
| 05 | 04 | 00 | Front Drive Half-Shaft Subsystem | 27.619 |
| 05 | 05 | 00 | Rear Drive Half Shaft Subsystem | 0.000 |
| 05 | 07 | 00 | 4WD Driveline Control System | 0.294 |
| | | | **Total System Mass=** | 183.818 |
| | | | **Total Vehicle Mass=** | 2454 |
| | | | **System Mass Contribution relative to Vehicle=** | 7.49% |

Materials for all components comprising the Silverado Driveline are represented in **Figure 4.1-1**. In terms of mass proportion, Steel was the top material used.




| | | Material Categories: |
|---|---|---|
| 90.2% | 165.843 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 6.9% | 12.763 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 2.0% | 3.746 | 6. Rubber |
| 0.1% | 0.237 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.7% | 1.229 | 9. Other |
| 100% | 183.818 | TOTAL |

**Figure 4.7-1: Baseline Material Breakdown for Driveline System**

**Table 4.7-2** summarizes mass and cost savings by subsystem. The systems largest savings were realized in the Rear Drive Housed Axle Subsystem. Significant mass savings were also found in the Front Drive Housed Axle Subsystem. Detailed system analysis resulted in 20.4 kg saved at a cost decrease of $38.01, resulting in a $1.86 per kg cost save.

**Table 4.7-2: Mass-Reduction and Cost Impact Table for Driveline System**

| System | Subsystem | Sub Subsystem | Description | Net Value of Mass-Reduction Ideas: Idea Select Level | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost / Kilogram $/kg | System/ Subsystem Mass-Reduction "%" | Vehicle Mass-Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 05 | 00 | 00 | Driveline System | | | | | | |
| 05 | 01 | 00 | Driveshaft Subsystem | A | 2.102 | $3.38 | $1.61 | 14.69% | 0.09% |
| 05 | 02 | 00 | Rear Drive Housed Axle Subsystem | A | 10.473 | $25.78 | $2.46 | 11.76% | 0.43% |
| 05 | 03 | 00 | Front Drive Housed Axle Subsystem | A | 6.486 | $6.27 | $0.97 | 12.35% | 0.26% |
| 05 | 04 | 00 | Front Drive Half-Shaft Subsystem | A | 1.356 | $2.58 | $1.90 | 4.91% | 0.06% |
| 05 | 05 | 00 | Rear Drive Half Shaft Subsystem | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 05 | 07 | 00 | 4WD Driveline Control System | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | A | 20.417 (Decrease) | $38.01 (Decrease) | $1.86 (Decrease) | 11.11% | 0.83% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.7.1 Driveshaft Subsystem

As seen in **Table 4.7-3**, the most significant contributor to the Driveshaft Subsystem mass is the rearward propeller shafts. This sub-subsystem comprises 4.1% of the subsystem mass.

**Table 4.7-3: Mass Breakdown by Sub-subsystem for Driveshaft Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| **05** | **01** | **00** | **Driveshaft Subsystem** | |
| 05 | 01 | 01 | Rearward Propeller Shafts | 7.514 |
| 05 | 01 | 05 | Forward Propeller Shaft | 6.798 |
| | | | | |
| | | | **Total Subsystem Mass =** | **14.312** |
| | | | **Total System Mass =** | **183.818** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **Subsystem Mass Contribution Relative to System =** | **7.79%** |
| | | | **Subsystem Mass Contribution Relative to Vehicle =** | **0.58%** |

#### 4.7.1.1 Chevrolet Silverado Driveline Subsystem Technology

The Silverado Driveshaft Subsystem is comprised of a front propshaft assembly with the yokes, and a rear propshaft assembly with the yokes. The shafts are tube material and the yokes are a forged material, in both steel and aluminum.

**Image 4.7-1: Silverado Front Propshaft and Yoke**
*(Source: FEV Photo)*

The front propshaft assembly is made of steel for both the shaft and the yokes. The rear propshaft was an aluminum assembly with added metal for rotational strength to match the same as the steel shaft properties.

**Image 4.7-2: Silverado Rear Propshaft and Yoke**
*(Source: FEV Photo)*

### 4.7.1.2 Mass-Reduction Industry Trends

The use of carbon fiber was initially considered. In performing research the mass save was very near the aluminum mass and the cost was two to four times more expensive in some cases. The technology is not yet ready for mass-production.

Carbon fiber is a safer type of material for the driveshaft. If it were to fracture and break there would not be any penetration into the passenger compartment avoiding possible catastrophic injuries.

It lacks impact resistance which could be a root cause of failure. Impact resistance is considered a “have to have” in the propshaft material on a vehicle similar to the Silverado full size pickup truck.

With the rear propshaft being aluminum it is a short walk to manufacture the front propshaft from aluminum base material, adding aluminum volume to help increase torsional, rotational strength. The only issue with making this a reality is finding a way to maintain the packaging envelope of the front driveshaft. The use of aluminum requires more aluminum to maintain the torsional strength; this may only be accomplished by increasing the diameter. There are unique processes when it comes to manufacturing with different materials than historically used. The rear driveshaft has taken the leap of faith, it is thought the front will soon join it and be manufactured from aluminum or another lightweight material.

### 4.7.1.3 Summary of Mass Reduction Concepts Considered

During the brainstorming portion of our study of mass-reduction opportunities within the Chevrolet Silverado there were many areas analyzed and alternative materials became the focus to achieve mass-reduction. The ideas we identified were only thought starters which required further research and analysis to determine if they were viable mass production products which could be delivered by the 2025 new vehicle model year.

**Table 4.7-4: Summary of Mass Reduction Concepts Initially Considered for the Driveline Subsystem**

| Component / Assembly | Mass- Reduction Idea | Estimated Impact | Risks & Trade Offs and / or Benefits |
|---|---|---|---|
| Front Propshaft Assembly | Change material from Steel to Aluminum | 50% Mass-Reduction | 14% Cost Reduction<br>Silverado has an Aluminum Rear Propshaft<br>Minimal Risk |

### 4.7.1.4 Selection of Mass Reduction Ideas

**Table 4.7-5** lists the mass reduction ideas applied to Driveshaft Subsystem.

**Table 4.7-5: Mass Reduction Ideas Selected for Driveshaft Subsystem**

| System | Subsystem | Sub Subsystem | System Sub-System Description | Mass-Reduction Ideas Selected for Detailed Evaluation |
|---|---|---|---|---|
| 05 | 01 | 00 | Drivshaft | |
| 05 | 01 | 05 | Forward Propshaft Assembly | Change material form Steel (base) to Aluminum (new). |

**Table 4.7-6: Mass reduction and Cost Impact for Driveshaft Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys./ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 05 | 01 | 00 | Driveshaft | | | | | | |
| 05 | 01 | 01 | Rearward Propeller Shaft | | 0.00 | $0.00 | -- | -- | 0.00% |
| 05 | 01 | 05 | Forward Propeller Shaft | | 2.10 | $3.38 | $1.61 | 30.92% | 0.09% |
| | | | | A | 2.10 (Decrease) | $3.38 (Decrease) | $1.61 (Decrease) | 14.69% | 0.09% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.7.2 Rear Drive Housed Axle Subsystem

#### 4.7.2.1 Subsystem Content Overview

As shown in **Table 4.7-7**, the most significant contributor to the Rear Drive Housed Axle Subsystem is the Beam Rear Axle Assembly, comprising 66.6% of the Rear Drive Housed Axle Subsystem.

**Table 4.7-7: Mass Breakdown by Sub-subsystem for Rear Drive Housed Axle Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 05 | 02 | 00 | Rear Drive Housed Axle Subsystem | |
| 05 | 02 | 01 | Beam Rear Axle Assembly | 66.598 |
| 05 | 02 | 04 | Rear Drive Unit | 7.563 |
| 05 | 02 | 05 | Rear Axle Differential Carrier Assy | 14.906 |
| | | | | |
| | | | Total Subsystem Mass = | 89.067 |
| | | | Total System Mass = | 183.818 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 48.45% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 3.63% |

#### 4.7.2.2 Chevrolet Silverado Baseline Subsystem Technology

The Silverado Rear Drive Housed Axle Subsystem is common to this type of rear drive truck system. There is solid rear steel axle shaft accompanied by a common rear axle drive unit.

#### 4.7.2.3 Mass Reduction Industry Trends

Axles are typically made from SAE grade 41xx steel or SAE grade 10xx steel. SAE grade 41xx steel is commonly known as chrome-molybdenum steel (or "chrome-moly") while SAE grade 10xx steel is known as carbon steel. The primary differences between the two are that chrome-moly steel is significantly more resistant to bending or breaking, but is very difficult to weld with tools normally found outside a professional welding shop.

#### 4.7.2.4 Summary of Mass Reduction Concepts Considered

**Table 4.7-8** lists the mass reduction ideas considered for the Rear Drive Housed Axle Subsystem.

**Table 4.7-8: Mass Reduction Ideas Considered for the Rear Drive Housed Axle Subsystem**

| Component / Assembly | Mass- Reduction Idea | Estimated Impact | Risks & Trade Offs and / or Benefits |
|---|---|---|---|
| Rear Axle Housing | Varilite® Manufacturing Process (US Manufacturing, Corporation) | 20% Mass-Reduction | 12% Cost Reduction Currently used on Ford F-Series |
| Rear Axle Housing Differential Case Cover | Change material from Steel to Aluminum | 50% Mass-Reduction | Minimal Cost Reduction Minimal Risk |
| Rear Axle Shaft | Varilite® Manufacturing Process (US Manufacturing, Corporation) | 20% Mass-Reduction | 12% Cost Reduction Currently used on Ford F-Series |
| Rear Wheel Hub | Remove Mass on Wheel Hub | 5% Mass-Reduction | Minimal Risk |
| Rear Axle Differential | Schaeffler Group Lightweight Replacement | 30% Mass-Reduction | Technology still in vehicle testing Technology should be available before 2025 |
| Rear Axle Differential | Material Removal through Design Change Compliments Schaeffler | 25% Mass-Reduction | Minimal Risk |
| Rear Axle Differential | Welded Ring Gear Assembly (reduces mass of ring gear and | 13% Mass-Reduction | Minimal Risk Currently available on the marketplace |

#### 4.7.2.5 Selection of Mass Reduction Ideas

**Table 4.7-9** lists mass reduction ideas applied Rear Drive Housed Axle Subsystem.

**Table 4.7-9: Mass Reduction Ideas Selected for Rear Drive Housed Axle Subsystem**

| System | Subsystem | Sub Subsystem | System Sub-System Description | Mass-Reduction Ideas Selected for Detailed Evaluation |
|---|---|---|---|---|
| | | | | |
| 05 | 02 | 00 | **Rear Drive Housed Axle Subsystem** | |
| 05 | 02 | 01 | **Beam Rear Axle Assembly** | Strategically thin steel axle housing tube walls along entire length. |
| | | | | Change solid steel axle shaft (base) to steel tube axle shaft (new) and then strategically thin the tube walls (new). |
| | | | | Change rear axle differential housing cover material from Steel (base) to Aluminum (new). |
| 05 | 02 | 04 | **Rear Drive Unit** | Incorporate the Schaeffler Groups Lightweight differential assembly (new), replacing the cast iron and steel (base). |
| | | | | To compliment the differential change, the ring gear can also be downsized due to application. |
| | | | | |

The Silverado Rear Drive Housed Axle Subsystem provided many opportunities for mass-reduction. This Subsystem is divided into two sub subsystems, the first one being the Beam Rear Axle Assembly, the other the Rear Drive Unit.

The Beam Rear Axle Assembly provided an opportunity to strategically thin the walls of the axle tubing without losing any structural integrity. This is achieved through a proprietary extrusion process used to manufacture the tube sleeves. This process is known as the Vari-lite® tube process and U.S. Manufacturing Corporation is the owner of the process. The process is an extrusion process which begins with steel tube stock and through a series of different machining process creates a unique profile inside of the tube. This extrusion process maintains the same structural properties as the parent tube material, yet reduces the mass by ~20% per axle housing.  US Manufacturing axle tube assmblies are in production on Ford and  Dodge pickup trucks today.

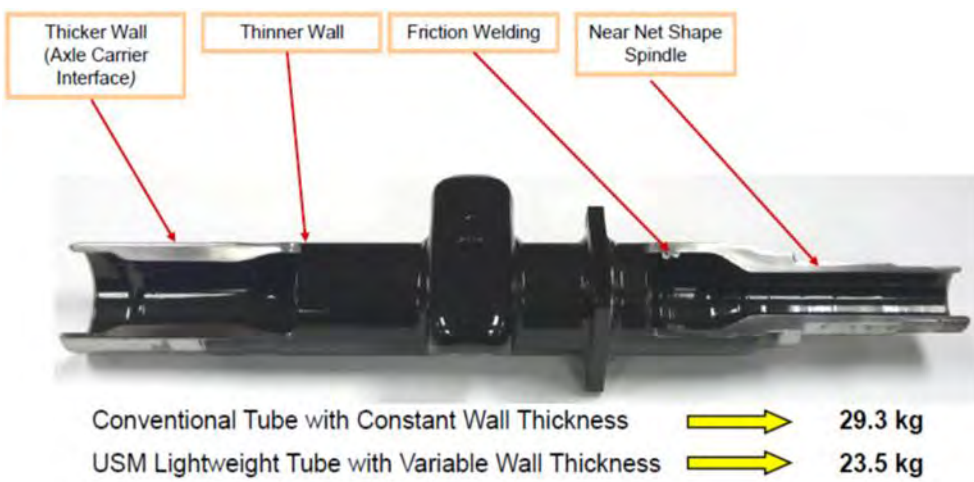



**Image 4.7-3: Near Net Shape Vari-Lite® Tube - Axle Housing**
*(Source: U.S. Manufacturing)*

The same conceptual process is used for the extrusion of the axle shafts. These components yield a little more mass savings, around 25% per axle assembly. These are produced by the same manufacturer as the rear axle housing tubing. Coupled with the axle shaft, the wheel hub was also mass-reduced by drilling six additional holes in the forging. Hollow axle shafts, produced using the US Manufacturing process, are also in production on Ford pickup trucks as well as a GM sport utility vehicle.

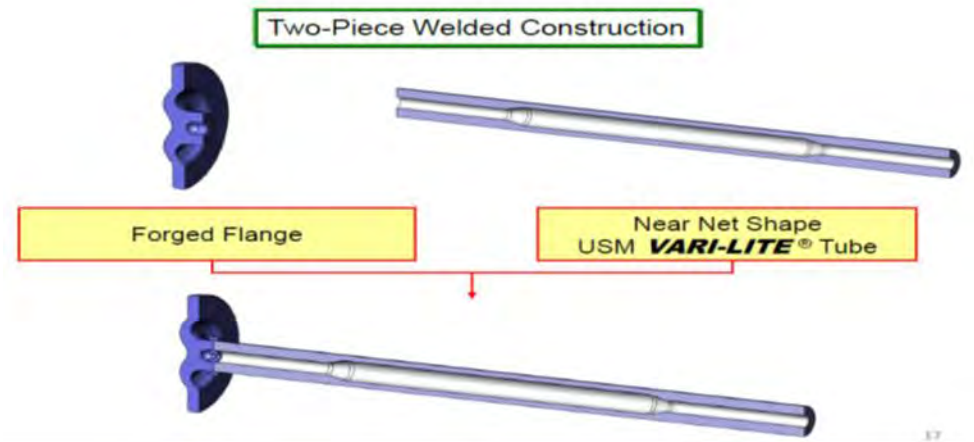



**Figure 4.7-2: Near Net Shape Vari-Lite® Tube – Axle Shaft**
*(Source: U.S. Manufacturing)*

Another opportunity was to change the rear axle differential housing cover from sheet steel to sheet aluminum. This provided an additional 1.101 kg mass reduction.

Through some research an opportunity presented itself in the form of a new configuration of the differential as we currently know it. The Schaeffler Group, Troy, Michigan, has developed a new lightweight concept for the transfer of energy from the propshaft to the axle shafts. The traditional cast differential housing has gone home to rest and a newly engineered product delivered by The Schaeffler Group. The differential casting has been redesigned as a stamped housing and two identical halves are riveted together. The Ring Gear is then bolted onto the mounting flanges featured on the stamped housing. This change also allowed for mass reduction of the ring gear due to different design. The surface of the old bolt flange is reduced in mass with this design along with fewer mounting bolts (6 versus 10).

**Image 4.7-4: Base Silverado (left) / Schaeffler Group (right) Differentials**
*(Sources:Left – FEV, Inc.; Right – Courtesy of the Schaeffler Group)*

Another opportunity which is presented with the Schaeffler Group redesign is packaging space. It was first developed for cramped space conditions on FWD vehicles. The design is very compact and is currently on test for RWD applications.

### 4.7.3 Front Drive Housed Axle Subsystem

**Table 4.7-10: Mass Reduction and Cost Impact for Front Drive Housed Axle Subsystem**

| System | Subsystem | Sub Subsystem | Description | Net Value of Mass-Reduction Ideas: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 05 | 03 | 04 | **Front Drive Housed Axle Subsystem** | | | | | | |
| 05 | 03 | 04 | Front Differential Ring Gear | | 1.22 | $5.50 | $4.52 | 2.32% | 0.05% |
| 05 | 03 | 04 | Front Differential | | 1.25 | -$0.02 | -$0.02 | 2.38% | 0.05% |
| 05 | 03 | 04 | Front Differential Mounting Bracket LH | | 1.81 | $2.71 | $1.49 | 3.45% | 0.07% |
| 05 | 03 | 04 | Front Differential Mounting Bracket RH | | 1.33 | $1.83 | $1.38 | 2.53% | 0.05% |
| 05 | 03 | 04 | Front Differential Output Shaft | | 0.876 | -$3.76 | -$4.29 | 1.67% | 0.04% |
| | | | | A | **6.5** (Decrease) | **$6.26** (Decrease) | **$0.97** (Decrease) | **12.35%** | **0.26%** |

**(1) "+" = Mass Decrease, "-" = Mass Increase**
**(2) "+" = Cost Decrease, "-" = Cost Increase**

#### 4.7.3.1 Subsystem Content Overview

**Table 4.7-11: Mass Breakdown by Sub-subsystem for Front Drive Housed Axle Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 05 | 03 | 00 | Front Drive Housed Axle Subsystem | |
| 05 | 03 | 04 | Front Drive Unit | 52.526 |
| | | | Total Subsystem Mass = | 52.526 |
| | | | Total System Mass = | 183.818 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 28.57% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 2.14% |

#### 4.7.3.2 Chevrolet Silverado Baseline Subsystem Technology

The Silverado Front Drive Housed Axle Subsystem is common to this type of front drive truck system.

#### 4.7.3.3 Summary of Mass Reduction Concepts Considered

**Table 4.7-12** lists the mass reduction ideas considered for the Front Drive Housed Axle Subsystem.

**Table 4.7-12: Mass Reduction Ideas Considered for the Front Drive Housed Axle Subsystem**

| Component / Assembly | Mass- Reduction Idea | Estimated Impact | Risks & Trade Offs and / or Benefits |
|---|---|---|---|
| Front Axle Differential | Schaeffler Group<br>Lightweight Replacement | 30% Mass-Reduction | Technology still in vehicle testing<br>Technology should be available before 2025<br>Original modification was on a FWD Differential |
| Front Axle Differential | Material Removal through Design Change<br>Compliments Schaeffler Lightweight Differential | 25% Mass-Reduction | Minimal Risk |
| Front Axle Differential | Welded Ring Gear Assembly<br>(reduces mass of ring gear and bolts) | 13% Mass-Reduction | Minimal Risk<br>Currently available on the marketplace |

#### 4.7.3.4 Selection of Mass Reduction Ideas

**Table 4.7-13: Mass Reduction Ideas Selected for Front Drive Housed Axle Subsystem**

| System | Subsystem | Sub Subsystem | System Sub-System Description | Mass-Reduction Ideas Selected for Detailed Evaluation |
|---|---|---|---|---|
| | | | | |
| 05 | 00 | 00 | **Driveline System** | |
| 05 | 03 | 04 | **Front Drive Housed Axle** | differential assembly (new), replacing the cast iron and steel (base). |
| | | | | To compliment the differential change, the ring gear can also be downsized due to application. |
| | | | | Change the front differential housing support brackets from Forged steel (base) to Forged Aluminum(new). |
| | | | | shaft (new) and then strategically thin the tube walls (new). |
| | | | | |

The Front Drive Housed Axle Subsystem offered a fair amount of mass-reduction opportunities. The axle housing itself had already taken some strides to mass-reduction. The entire axle casing and differential housing were made of die cast aluminum.

Similar to the rear axle drive unit, the front axle differential offered a 1.93 kg mass reduction through taking advantage of the Schaeffler Group's redesigned differential assembly. The new design streamlines the profile of the differential, reduces the overall mass, and packages in a smaller area.


**Image 4.7-5: Base Silverado Front Differential (Left); Light-Weight Differential (Right)**
*(Source:Left – FEV, Inc.; Right – Provided by Schaeffler Group)*

This change also allows for the ring gear to be slightly lightened, just as the rear differential. The ring rear mass reduction is less than the rear differential mass-reduction due to the slightly lighter requirements off the entire differential.

Additional mass-reduction was provided in the differential mounting brackets. The change of material from forged steel to forged aluminum yielded a combined mass saving of 3.14 kg.

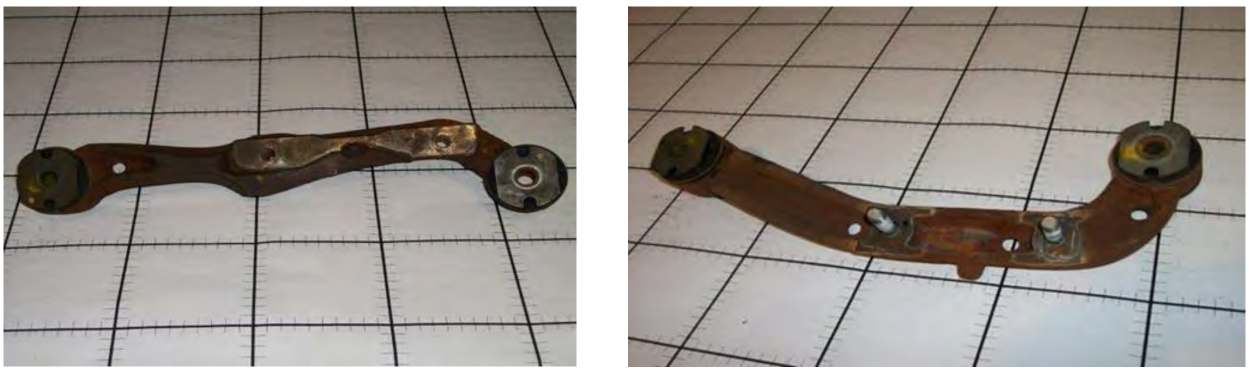


**Image 4.7-6: LH and RH Front Differential Mounting Brackets**
*(Source: FEV, Inc.)*

The Front Differential Carrier output shaft is an opportunity for mass-reduction. It is a solid steel shaft which couples the differential to the axle shaft and onward to the wheels.

The opportunity with this shaft is the same as the axle shafts previously discussed. The mass-reduction technology employed is the strategic thinning of the shaft walls using the manufacturing example provided by U. S. Manufacturing, located in Warren, Michigan. This process change and mass-reduction yields a 1.12 kg mass-reduction.

**Table 4.7-14: Mass Reduction and Cost for Front Drive Housed Axle Subsystem**

| System | Subsystem | Sub Subsystem | Description | Net Value of Mass-Reduction Ideas: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 05 | 03 | 04 | Front Drive Housed Axle Subsystem | | | | | | |
| 05 | 03 | 04 | Front Differential Ring Gear | | 1.22 | $5.50 | $4.52 | 2.32% | 0.05% |
| 05 | 03 | 04 | Front Differential | | 1.25 | -$0.02 | -$0.02 | 2.38% | 0.05% |
| 05 | 03 | 04 | Front Differential Mounting Bracket LH | | 1.81 | $2.71 | $1.49 | 3.45% | 0.07% |
| 05 | 03 | 04 | Front Differential Mounting Bracket RH | | 1.33 | $1.83 | $1.38 | 2.53% | 0.05% |
| 05 | 03 | 04 | Front Differential Output Shaft | | 0.876 | -$3.76 | -$4.29 | 1.67% | 0.04% |
| | | | | A | 6.5 (Decrease) | $6.26 (Decrease) | $0.97 (Decrease) | 12.35% | 0.26% |

(1) "+" = Mass Decrease, "-" = Mass Increase
(2) "+" = Cost Decrease, "-" = Cost Increase

## 4.7.4 Front Drive Half-Shaft Subsystem

### 4.7.4.1 Subsystem Content Overview

**Table 4.7-15: Mass Breakdown by Sub-subsystem for Front Drive Half-Shafts Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 05 | 04 | 00 | Front Drive Half-Shafts Subsystem | |
| 05 | 04 | 01 | Front Half Shaft | 27.619 |
| | | | Total Subsystem Mass = | 27.619 |
| | | | Total System Mass = | 183.818 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 15.03% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.13% |

#### 4.7.4.2 Chevrolet Silverado Baseline Subsystem Technology

The drive to the two axles and may also have included reduction gears, a dog clutch or differential. At least two drive shafts were used, one from the transfer case to each axle. In some larger vehicles, the transfer box was centrally mounted and was itself driven by a short drive shaft.

#### 4.7.4.3 Summary of Mass Reduction Concepts Considered

**Table 4.7-16: Mass Reduction Ideas Considered for the Front Drive Half-Shaft Subsystem**

| Component / Assembly | Mass- Reduction Idea | Estimated Impact | Risks & Trade Offs and / or Benefits |
|---|---|---|---|
| Front Differential Output Shaft | Varilite® Manufacturing Process (US Manufacturing, Corporation) | 20% Mass-Reduction | Minimal Risk |
| Front Half-Shafts | Varilite® Manufacturing Process (US Manufacturing, Corporation) | 20% Mass-Reduction | 12% Cost Reduction<br>Currently used on Ford F-Series |
| Front Differential Mounting Brackets | Change from Forged Steel to Forged Aluminum | 50% Mass-Reduction | Minimal Risk |
| Front Wheel Hub | Remove Mass on Wheel Hub | 5% Mass-Reduction | Minimal Risk |

**Table 4.7-17: Mass Reduction Ideas Selected for Front Drive Half-Shaft Subsystem**

| System | Subsystem | Sub Subsystem | System Sub-System Description | Mass-Reduction Ideas Selected for Detailed Evaluation |
|---|---|---|---|---|
| | | | | |
| **05** | **04** | **00** | **Front Drive Half-Shafts Subsystem** | |
| 05 | 04 | 01 | **Front Drive Half-Shaft** | Change solid steel axle half shaft (base) to steel tube axle half shaft (new) and then strategically thin the tube walls. |
| | | | | Remove mass from the wheel hub by drilling lightening holes . |
| | | | | |

**Image 4.7-7: Chevrolet Silverado Half Shaft Assembly, Disassembled**
*(Source: FEV, Inc.)*

The front axle half-shafts are very simple yet complex pieces of the driveline puzzle. They are simple straight shafts of solid steel in the Chevrolet Silverado, and splined at both ends. They are complex in how they interface with their mating puzzle pieces. They mate with a constant velocity assembly on the wheel end, and a unique variable pitch type joint on the differential end. **Image 4.7-8** is the entire half-shaft assembly on the Silverado. The wheel end is on the right hand side of the picture.

The attachment point to the differential output shaft is on the left hand side of the image. This bolts directly to the front differential output shaft. There are three precision roller bearings which maintain constant engagement with the hub. The precision roller bearings allow for continuous movement of the shaft and allows it to comply to the various angles the independent suspension part of the assembly can present.

The attachment point on the wheel end is much different and complex with tightly toleranced components. As you can see there are six precision ground balls which are captured in the bearing type assembly and retained by the cage like piece. This assembly provides the wheel end with the same type of flexibility provided on the differential output joint. The goal of the assembly is to maintain constant velocity of the axle to the wheel hub, maintaining proper vehicle performance.

The strategic thinning of the tube walls using the U.S. Manufacturing Corporation extrusion process allows for a mass-reduction of 1.12 kg.

**Image 4.7-8: Vari-Lite® Tube – Axle Half-Shaft**
*(Source: U.S. Manufacturing)*

**Table 4.7-18: Driveline System Mass-Reduction & Cost Impact**

| System | Subsystem | Sub Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass-Reduction Ideas | | | | | |
| 05 | 04 | 01 | Front Drive Half-Shaft Subsystem | | | | | | |
| 05 | 04 | 01 | Front Half-Shafts | | 1.12 | $3.11 | $2.77 | 4.07% | 0.05% |
| 05 | 04 | 01 | Front Axle Wheel Hub | | 0.232 | -$0.54 | -$2.33 | 0.84% | 0.01% |
| | | | | A | 1.4 (Decrease) | $2.57 (Decrease) | $1.90 (Decrease) | 4.91% | 0.06% |

(1) "+" = Mass Decrease, "-" = Mass Increase
(2) "+" = Cost Decrease, "-" = Cost Increase

### 4.7.5 Secondary Mass Reduction / Compounding

This report identifies mass reduction alternatives and cost implications for the Driveline System with the intent to meet the function and performance requirements of the baseline vehicle (2011 Chevrolet Silverado).

The Driveline Subsystem contributed a system mass reduction of 20.5 kg. This mass reduction provided a vehicle cost save of $38.01, which equates to $1.86 per kg. The overall vehicle mass reduction contribution is 0.83%. **Table 4.7-19** is a summary of the calculated mass reduction and cost impact for each vehicle subsystem evaluated. There are no compounding mass reductions for this system.

**Table 4.7-19: Mass-Reduction and Cost Impact Summary**

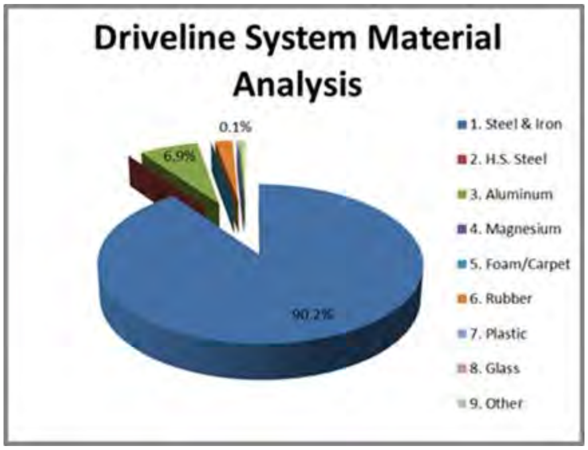
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction | | | | | | | |
| 05 | 00 | 00 | **Driveline System** | | | | | | | | |
| 05 | 01 | 00 | Driveshaft Subsystem | 2.10 | 0.00 | 2.10 | $3.38 | $0.00 | $3.38 | $1.61 | 0.09% |
| 05 | 02 | 00 | Rear Drive Housed Axle Subsystem | 10.5 | 0.00 | 10.5 | $25.78 | $0.00 | $25.78 | $2.46 | 0.43% |
| 05 | 03 | 00 | Front Drive Housed Axle Subsystem | 6.49 | 0.00 | 6.49 | $6.27 | $0.00 | $6.27 | $0.97 | 0.26% |
| 05 | 04 | 00 | Front Drive Half-Shaft Subsystem | 1.36 | 0.00 | 1.36 | $2.58 | $0.00 | $2.58 | $1.90 | 0.06% |
| 05 | 05 | 00 | Rear Drive Half Shaft Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 05 | 07 | 00 | 4WD Driveline Control System | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| | | | | **20.4** (Decrease) | **0.00** | **20.4** (Decrease) | **$38.01** (Decrease) | **$0.00** | **$38.01** (Decrease) | **$1.86** (Decrease) | **0.83%** |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.7.6 Driveline System Material Analysis

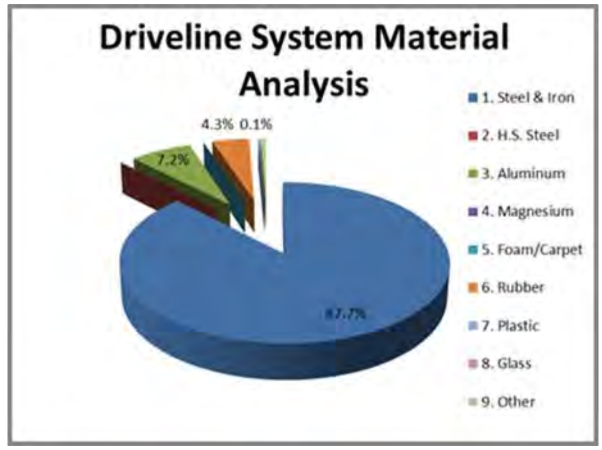
**Figure 4.7-3** provides the material distribution mass reduction savings generated from the base vehicle to the mass reduction model, resulting in 20.417 kg mass reduction for the entire subsytem. “Steel & Iron” decreased from 165.8 kg to 143.4 kg. “Aluminum” was decreased a kg. “Rubber,” meanwhile, increased from 3.75 kg to 7.07 kg.

**Baseline Driveline System**




| | | Material Categories: |
|---|---|---|
| 90.2% | 165.843 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 6.9% | 12.763 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 2.0% | 3.746 | 6. Rubber |
| 0.1% | 0.237 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.7% | 1.229 | 9. Other |
| 100% | 183.818 | TOTAL |

**Total Mass Reduced Drivline System**




| | | Material Categories: |
|---|---|---|
| 87.7% | 143.366 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 7.2% | 11.760 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 4.3% | 7.073 | 6. Rubber |
| 0.1% | 0.237 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.6% | 0.965 | 9. Other |
| 100% | 163.401 | TOTAL |

**Figure 4.7-3: Baseline and Total Mass Reduced Drivline System Material Content**

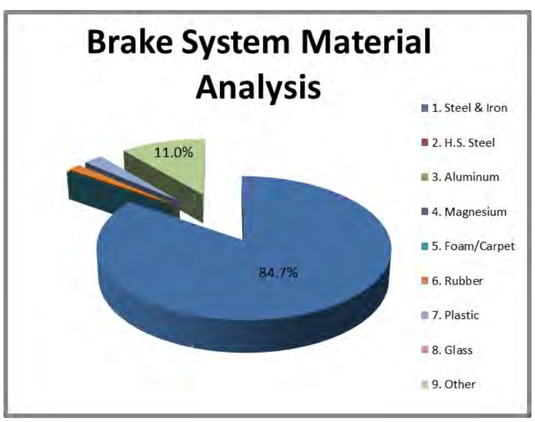
## 4.8 Brake System

As shown in **Table 4.8-1**, the Brake System is composed of six subsystems: Front Rotor/Drum and Shield; Rear Rotor/Drum and Shield; Parking Brake and Actuation; Brake Actuation; Power Brake; and Brake Controls Subsystems. In comparing the six subsystems, the greatest mass, 43 kg, is located in the Front Rotor/Drum and Shield Subsystem which accounts for approximately 42.6% of the entire Brake System.

**Table 4.8-1: Baseline Subsystem Breakdown for the Brake System**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 06 | 00 | 00 | Brake System | |
| 06 | 03 | 00 | Front Rotor/Drum and Shield Subsystem | 43.0 |
| 06 | 04 | 00 | Rear Rotor/Drum and Shield Subsystem | 34.3 |
| 06 | 05 | 00 | Parking Brake and Actuation Subsystem | 4.70 |
| 06 | 06 | 00 | Brake Actuation Subsystem | 10.7 |
| 06 | 07 | 00 | Power Brake Subsystem (for Hydraulic) | 4.24 |
| 06 | 09 | 00 | Brake Controls Subsystem | 4.17 |
| | | | | |
| | | | | |
| | | | | |
| | | | Total System Mass = | 101.0 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 4.12% |

The Material Categories for the Baseline Brake System are shown in **Figure 4.8-1**. "Steel & Iron" is the leading category, with 84.7% (85.6 kg) of the overall mass, followed by "Other" at 11% (11.2 kg), and "Plastic" at 2.5% (2.5 kg). The "Other" category includes assemblies that have multiple materials, such as switches and relays.




| | | Material Categories: |
|---|---|---|
| 84.7% | 85.6 | 1. Steel & Iron |
| 0.0% | 0.0 | 2. H.S. Steel |
| 0.0% | 0.0 | 3. Aluminum |
| 0.0% | 0.0 | 4. Magnesium |
| 0.038% | 0.0 | 5. Foam/Carpet |
| 1.71% | 1.72 | 6. Rubber |
| 2.51% | 2.53 | 7. Plastic |
| 0.0% | 0.0 | 8. Glass |
| 11.0% | 11.2 | 9. Other |
| 100% | 101.0 | TOTAL |

**Figure 4.8-1: Baseline Brake System Material Distribution**

The Final Calculated Results Summary for the entire Chevrolet Silverado Brake System is shown in **Table 4.8-2**. This combination of proposed solutions were selected for this cost group due to the significant weight savings that were calculated to be 43.9 kg with a $167.87 overall cost increase.

**Table 4.8-2: Mass Reduction and Cost Impact for the Brake System**

| | | | | Net Value of Mass Reduction Ideas | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | System/ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | 2454 | | | | | | |
| 06 | 00 | 00 | **Brake System** | | | | | | |
| 06 | 03 | 00 | Front Rotor/Drum and Shield Subsystem | D | 22.0 | -$56.20 | -$2.55 | 21.8% | 0.90% |
| 06 | 04 | 00 | Rear Rotor/Drum and Shield Subsystem | D | 16.3 | -$71.02 | -$4.35 | 16.1% | 0.66% |
| 06 | 05 | 00 | Parking Brake and Actuation Subsystem | X | 1.45 | -$15.56 | -$10.72 | 1.44% | 0.06% |
| 06 | 06 | 00 | Brake Actuation Subsystem | B | 2.53 | -$0.46 | -$0.18 | 2.50% | 0.10% |
| 06 | 07 | 00 | Power Brake Subsystem (for Hydraulic) | X | 1.58 | -$24.64 | -$15.57 | 1.57% | 0.06% |
| | | | | | | | | | |
| | | | | D | 43.9 (Decrease) | -$167.87 (Increase) | -$3.83 (Increase) | 43.4% | 1.79% |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

## 4.8.1 Front Rotor/Drum and Shield Subsystem

### 4.8.1.1 Subsystem Content Overview

**Figure 4.8-2** represents the major brake components in the Front Rotor/Drum and Shield Subsystem and their relative location and position relevant to one another as located on the vehicle front corner.

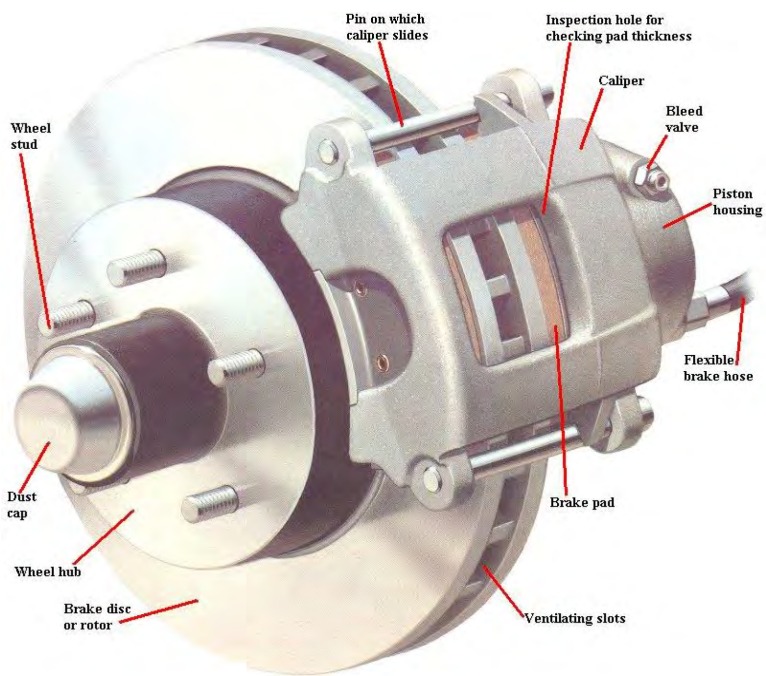



**Figure 4.8-2: Front Rotor / Drum and Shield Subsystem Relative Location Diagram**
*(Source: http://www.motorera.com/dictionary/di.htm)*

As seen in **Image 4.8-1**, the Front Rotor/Drum and Shield Subsystem consists of the major components of the front rotor, front splash shield, front caliper assembly, front caliper mounting, and miscellaneous anchor and attaching components.

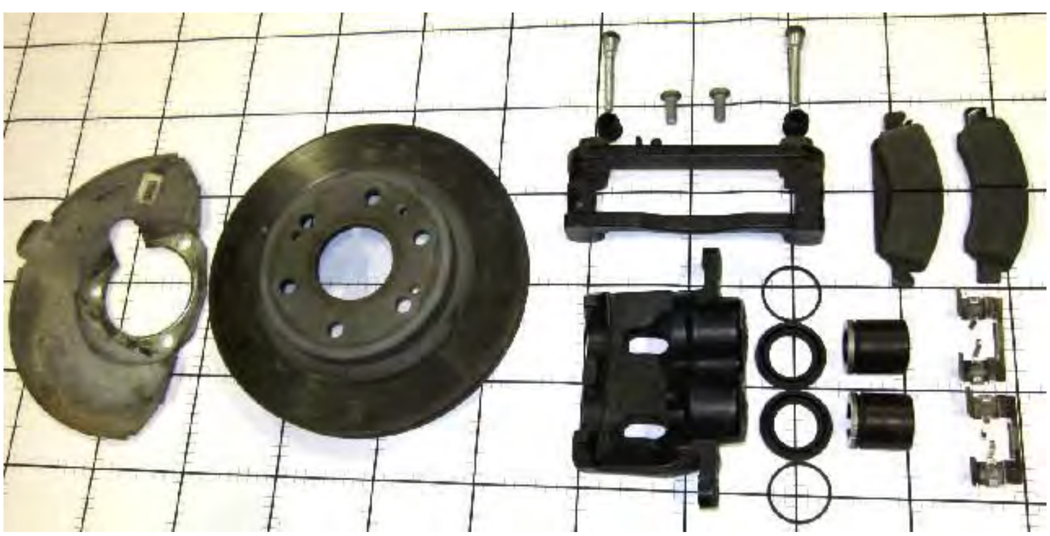


**Image 4.8-1: Front Rotor / Drum and Shield Subsystem Current Major Components**
*(Source: FEV, Inc.)*

**Table 4.8-3** indicates the two sub-subsystems that make-up the Front Rotor/Drum and Shield Subsystem. These are the Front Rotor and Shield Sub-subsystem and the Anchor and Attaching Components Sub-subsystem. The most significant contributor to the mass within this subsystem was found to be within the Front Rotor and Shield Sub-subsystem (approximately 56.5%).

**Table 4.8-3: Mass Breakdown by Sub-subsystem for the Front Rotor / Drum and Shield Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 06 | 03 | 00 | Front Rotor/Drum and Shield Subsystem | |
| 06 | 03 | 01 | Front Rotor and Shield | 24.3 |
| 06 | 03 | 02 | Front Caliper, Anchor and Attaching Components | 18.7 |
| | | | Total Subsystem Mass = | 43.0 |
| | | | Total System Mass = | 101.0 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 42.6% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.75% |

#### 4.8.1.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado Front Rotor and Shield Subsystem (**Image 4.8-2**) follows typical industry standards for design and performance. The rotors (**Image 4.8-3**) are single piece, vented design cast out of grey iron and manufactured to SAE specifications. The splash shields (**Image 4.8-4**) are typical stamped and vented steel fabrications. The caliper assembly (**Image 4.8-5**) is composed of several components, which included the caliper housings (**Image 4.8-6**) which are high nickel content cast iron with the appropriate machining. The caliper mountings, (**Image 4.8-7**) are cast iron and machined. The brake caliper assembly houses the brake pads and pistons. The caliper pistons (**Image 4.8-8**) are molded phenolic glass-filled plastic with standard seal configurations. The brake pads (**Image 4.8-9**) are of standard construction with steel backing plates and friction pad materials. The current OEM Chevrolet Silverado front brake corner assembly (**Image 4.8-2**) has a mass of 21.5 kg.

**Image 4.8-2: Front Brake System Current Assembly Example**
*(Source: http://www.imakenews.com/tituswillford)*

### 4.8.1.3 Mass Reduction Industry Trends

The disc brake system has been used in the automotive industry since the early 1900s. The disc brake system's primary parts are the rotor assembly and the caliper assembly. Standard automotive brake rotors also known as single piece rotors are sand casted from iron. The disc brake system, compared to the drum brake system, has better stopping performance, cools faster and is less susceptible to water immersion.

Until recently, there have been relatively little advancements made to the disc brake system. Over the years, engineers have made small changes that have helped with cooling and braking performance, but now companies are looking for new ways to lighten the vehicle and further protect the environment.

A recent advancement to the disc brake system is the introduction of the two-piece rotor. This new rotor design is made up of a rotor disc and a center hat or carrier. The hat is fastened to the disc using T-nuts or "floating buttons." The disc can be made of cast iron, but now engineers are looking to composites for greater weight savings and longer lasting disc life. The hat is usually made out of aluminum allowing for better cooling due to aluminums higher rate of heat dissipation and is lighter in weight. Because of the two-piece design, the disc is allowed to expand and contract without stressing the hat. This helps prevent the disc from warping or cracking.

Another new braking technology belongs to Siemens VDO and is called the Electronic Wedge Brake (EWB). This 12-volt electrically controlled braking system eliminates the need for hydraulics in the vehicle. The system is based on a wedge-shaped plate connected to a pair of electric motors that press the brake pads against the rotor. When the operator depresses the brake pedal, a signal is sent to the brake motor to activate the wedge plate. Within the braking system, an intelligent module and several sensors are used to monitor movement and force thus eliminating the need for the ABS system.

#### 4.8.1.3.1 Rotors

The baseline OEM Chevrolet Silverado front rotor (**Image 4.8-3**) is a single-piece, vented design cast from grey iron and has a mass of 11.7 kg. Many high performance and luxury vehicle models have begun utilizing alternate rotor designs in order to improve both performance and economy. Two-piece rotor assemblies are now found in many Mercedes, BMW, Audi, Porsche, and Chevrolet Corvettes across multiple platforms and models. This two-piece configuration was also mentioned in the March 2010 Lotus Report. Besides OEM's, there are aftermarket suppliers that use this design. Brembo and Wilwood are two such companies that have used this rotor design in various production applications. This two-piece design usually utilizes an aluminum center hub (or "hat") along with a disc braking surface (typically cast iron or steel).

**Image 4.8-3: Front Rotor Current Component**
*(Source: FEV, Inc.)*

The rotor center (hat) can be made from several material choices including aluminum, titanium, magnesium, grey iron or steel and manufactured from cast forms or billet machined from solid.

The rotor disc surfaces are also able to be made from various materials and processing methods. These include aluminum metal matrix composites (Al/MMC), metal matrix composites, titanium, and iron. Even carbon/ceramic matrices have been used to produce rotors of less mass. Processing includes casting vented or solid disc plates and the machining cross-drilled plates, slotted plates and scalloped disc diameters (both ID and OD) profiles.

Some racing cars and airplanes use brakes with carbon fiber discs and carbon fiber pads to reduce weight. For these systems, wear rates tend to be high, and braking may be poor or "grabby" until the brake is heated to the proper operating temperature. Again, this technology adds substantial costs if considered for regular high-volume automotive production capacities.

#### 4.8.1.3.2 Splash Shields

The baseline OEM Chevrolet Silverado front splash shield is a single-piece, non-vented design, stamped of common steel and has a mass of 0.478 kg. A majority of splash shields (or dust shields) (**Image 4.8-4**) are made from stamped, light-gage steel. Some are vented or slotted for reduced material usage and increased weight savings. Alternative materials are now beginning to be examined for use to further reduce weight contribution. These include aluminum, high-strength steels, and even various reinforced plastics.

**Image 4.8-4: Front Splash Shield Current Component**
*(Source: FEV, Inc.)*

#### 4.8.1.3.3 Caliper Assembly

The baseline OEM Chevrolet Silverado front caliper assembly is a multi-piece assembly with the major components being made from cast iron and has a mass of 8.76 kg. Traditionally caliper assemblies (**Image 4.8-5**) are comprised of several components. These include: housing, mounting, mounting attachment bolts (2), inboard brake pad and shim plate, outboard brake pad and shim plate, pistons (2), piston seal ring (2), piston seal boots (2), mounting slide pins (2), mounting slide pin boots (2), housing bleeder valve, and housing bleeder valve cap.


**Image 4.8-5: Front Caliper Current Assembly**
*(Source: http://cdn0.autopartsnetwork.com/images/catalog/brand/centric/640/14144280.jpg)*

##### *4.8.1.3.3.1 Housings*

The baseline OEM Chevrolet Silverado front caliper housing is a single piece cast iron design and has a mass of 4.80 kg. Traditionally caliper housings (**Image 4.8-6**) have been made from various grades of cast iron. This allowed for adequate strength while also acting as a heat sink to assist in the brake cooling function. Now with advances in materials and processing methods, other choices are available and being utilized in aftermarket and high performance applications as well as OEM vehicle markets. Among some of these alternate mediums are aluminum, titanium, steel, magnesium, and MMC. Forming methods now include sand cast, semi-permanent metal molding, die-casting, and machining from billet.

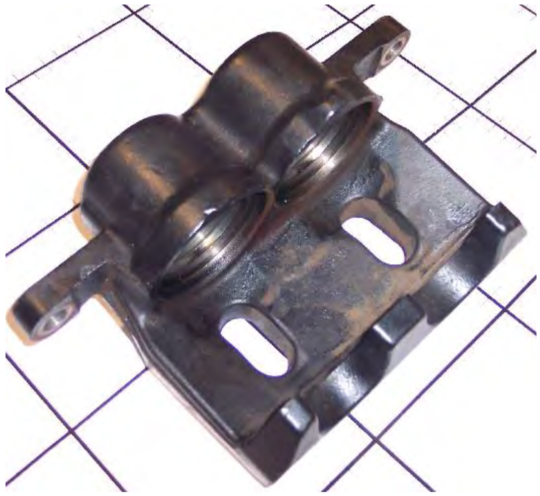


**Image 4.8-6: Front Caliper Housing Current Component**
*(Source: FEV, Inc.)*

While these alternatives now are designed with the strength and performance required, they do add a significant cost-versus-mass increase. However the weight savings achieved is quite substantial and assists with reducing vehicle requirements for suspension loads, handling, ride quality, engine horsepower requirements, etc. Other advanced development includes using bulk molding compound using long randomly oriented carbon fiber continues to be of interest due to the ability to easily mold it into complex shapes. However, temperature extremes encountered by brake components and the current cost of the material will be serious challenges for some time to come.

#### *4.8.1.3.3.2 Mountings*

The baseline OEM Chevrolet Silverado front caliper mounting (or bracket) is a single-piece cast iron design and has a mass of 2.18 kg. Caliper mountings (**Image 4.8-7**) have normally been made from various grades of cast iron for adequate strength and function. Now with advances in materials and processing methods other choices are available and being utilized in aftermarket and high performance applications as well as OEM vehicle markets. Among some of these alternate mediums are aluminum, titanium, steel, and magnesium. Forming and fabrication methods include casting and billet machining.

**Image 4.8-7: Front Caliper Mounting Current Component**
*(Source: FEV, Inc.)*

*4.8.1.3.3.3* *Pistons*

The baseline OEM Chevrolet Silverado front caliper pistons are a double piece phenolic glass-filled design with an aluminum band located at the piston opening and have a mass of 0.417 kg. Caliper pistons (**Image 4.8-8**) commonly are made from various alloys of steel for function and heat resistance. Now advances alternative materials and processing methods allow new choices to be available. Rather than metallics only (aluminum, steel, titanium) being utilized there are Phenolic glass-filled plastics that are used by OEMs in high volume. These are molded to near-net shape with minimal machining required, saving both material and processing time while saving significant mass.

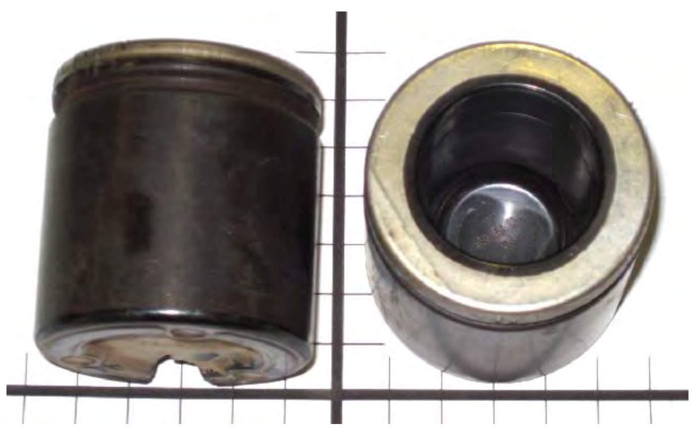


**Image 4.8-8: Front Caliper Piston Current Components**
*(Source: FEV, Inc.)*

*4.8.1.3.3.4* *Brake Pads*

The baseline OEM Chevrolet Silverado front caliper brake pads are of standard construction. They have a mass of 1.12 kg. The brake pads (**Image 4.8-9**) has had little change in design, materials or processing in recent years. Most have steel backing plates with a molded friction material attached to them. Various size braking surfaces and molded shapes are the common variations across different vehicle platforms. Most material differences are focused only in the friction material going from traditional asbestos now to semi-metallic and full metallics as well as various ceramic compounds. While these friction materials greatly affect performance and vehicle stopping distances under various conditions, little is accomplished in saving mass and reducing material weight.

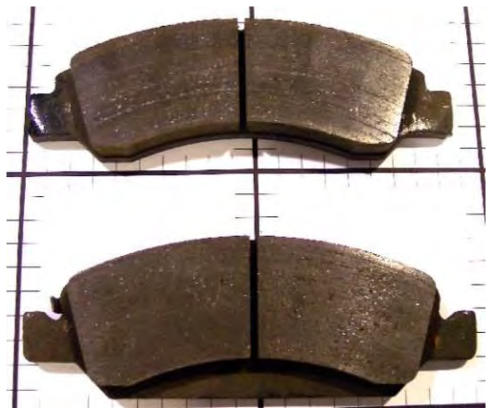


**Image 4.8-9: Front Caliper Brake Pad Current Components**
*(Source: FEV, Inc.)*

#### 4.8.1.4 Summary of Mass Reduction Concepts Considered

**Table 4.8-4** shows the mass reduction ideas considered from the brainstorming activity for the Front Rotor/Drum and Shield Subsystem and their various components. These ideas include part modifications, material substitutions, processing and fabrication differences, and use of alternative parts currently in production and used on other vehicles and applications.

**Table 4.8-4: Summary of Mass Reduction Concepts Considered – Front Rotor/Drum and Shield Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Front Rotor/Drum and Shield Subsystem** | | | |
| Rotor | Vent (slot) front rotors (1) | ~1% wt save | Low Risk - 5% cost increase |
| | Cross-Drill front rotors (2) | ~3% wt save | Low Risk - 5% cost increase |
| | Two piece Rotor - Aluminum center (hat) with Iron/Steel/CF outer surface (disc) w/ T-nut fasteners (3) | ~50% wt save | In production - 30% cost increase |
| | Change Material for Rotors - Al/MMC (4) | ~50% wt save | In production - 2.5x cost increase |
| | Downsizing based on Rotor fins added to hat (5) | ~5% wt save | Low Risk - 5% cost save |
| | Clearance drill holes in rotor top hat surface to reduce wt (6) | ~5% wt save | Low Risk - 5% cost increase |
| | Drill holes in rotor hat perimeter (7) | ~3% wt save | Low Risk - 5% cost increase |
| | Chg from straight to directional vanes btwn rotor disc surfaces (5%) (8) | ~5% wt save | Low Risk - 5% cost save |
| | Replace from comparable A2MAC1 database (9) | ~5% wt save | Low Risk - 5% cost save |
| | Change Material for Rotors - Carbon Ceramic (110) | ~60% wt save | In production - 4x cost increase |
| | Combine idea's 1, 2, 3, 4, 6 & 8 | ~50% wt save | ~4x cost increase |
| | Combine idea's 1, 2 & 6 | ~5% wt save | ~15% cost increase |
| | Combine idea's 1, 2, 3 & 6 | ~20% wt save | ~2x cost increase |
| | Combine idea's 1, 2, 3, 4 & 6 | ~60% wt save | ~35% cost increase |
| | Combine idea's 1, 2, 3, 6, 7, 8, 9 & 110 | ~50% wt save | ~15% cost increase |
| | | | |
| Splash Shield | Replace from comparable A2MAC1 database (10) | ~20% wt save | Low Risk - 20% cost save |
| | Make splash shield out of plastic (11) | ~40% wt save | ~2.5x cost increase |
| | Make splash shield out of HSS (12) | ~10% wt save | Low Risk - 3x cost increase |
| | Make splash shield out of Aluminum (13) | ~50% wt save | ~2x cost increase |
| | Make splash shield out of Titanium (14) | ~30% wt save | ~6.5x cost increase |
| | Add vent slots (.25"W x 2"L) (15) | ~5% wt save | Low Risk - 5% cost increase |
| | Combine 10, 11 & 15 | ~50% wt save | ~60% cost increase |
| | | | |
| Brake Pads | Replace from comparable A2MAC1 database (16) | ~10% wt save | In Production - ~10% cost save |
| | Make brake pad wear material thinner (17) | ~5% wt save | Low Production ~5% cost save |
| | Replace pad material w/ ceramic (109) | ~10% wt save | In Production - ~10% cost save |
| | Combine 16, 17 & 109 | ~25% wt save | ~25% cost save |

**Table 4.8-4 continued next page**

**Table 4.8-4 continued**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Front Rotor/Drum and Shield Subsystem** | | | |
| Calipers | Make caliper housing out of cast magnesium (18) | ~60% wt save | In Production - ~35% cost increase |
| | Make caliper housing out of cast aluminum (19) | ~50% wt save | In Production - ~25% cost increase |
| | Make caliper housing out of forged aluminum (20) | ~50% wt save | In Production - ~30% cost increase |
| | Replace from comparable A2MAC1 database (21) | ~15% wt save | In Production - ~10% cost save |
| | Combine 18 & 21 | ~65% wt save | Low Risk - Cost Neutral |
| | | | |
| Caliper Mounting Bracket | Make caliper bracket out of titanium (22) | ~35% wt save | In Production - ~5.5x cost increase |
| | Make caliper bracket out of cast magnesium (23) | ~40% wt save | In Production - ~35% cost increase |
| | Make caliper bracket out of cast aluminum (24) | ~50% wt save | In Production - ~30% cost increase |
| | Make caliper bracket out of forged aluminum (25) | ~50% wt save | In Production - ~35% cost increase |
| | Replace from comparable A2MAC1 database (26) | ~20% wt save | In Production - ~20% cost save |
| | Combine 23 & 26 | ~60% wt save | ~15% cost increase |

### 4.8.1.5 Selection of Mass Reduction Ideas

**Table 4.8-5** shows the mass reduction ideas for the Front Rotor/Drum and Shield Subsystem that were selected for detailed evaluation of both the mass savings achieved and the cost to manufacture them. Several ideas suggest plastics and magnesium as alternate materials. Also, included are part substitutions from other vehicle designs such as the Ford F150, 2006 Dodge RAM, and the 2002 Chevrolet Avalanche.

**Table 4.8-5: Mass Reduction Ideas Selected for the Detailed Front Rotor / Drum and Shield Subsystem Analysis**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|---|---|---|
| 06 | 03 | 00 | Front Rotor/Drum and Shield Subsystem | |
| 06 | 03 | 00 | Rotor | Downsize based on 2006 Dodge RAM |
| | | | | Two Piece Rotor - Aluminum center (hat) |
| | | | | Change disc material to Al/MMC |
| | | | | Change vanes from straight to directional |
| | | | | Cross-drill disc surface |
| | | | | |
| 06 | 03 | 00 | Front Splash Shields | Downsize based on 2007 Ford F150 |
| | | | | Make splash shield out of plastic |
| | | | | Add vent slots |
| | | | | |
| 06 | 03 | 00 | Caliper Housing | Downsize based on 2002 Chevy Avalanche |
| | | | | Make out of cast magnesium |
| | | | | |
| 06 | 03 | 00 | Caliper Mounting Bracket | Downsize based on 2012 Dodge Durango |
| | | | | Make out of cast magnesium |

4.8.1.5.1 <u>Rotors</u>

The solution(s) chosen to be implemented on the final front rotor assembly (**Image 4.8-10**) was the combination of multiple individual brainstorming ideas. These ideas included the following modifications to component design, material utilized and processing methods required:

- Two-piece Assembled Rotor Design, **Image 4.8-10**
  - Hat Fastened to Rotor Disc w/ T-Nuts and Bolts

    (Increased Process Time but Allows Better Hat Material Choices for Mass Savings)
  - Manufacturers and OEMs include: Chevrolet, Mercedes, Audi, BMW, Wilwood, Brembo


**Image 4.8-10: Front Rotor Mass Reduced Component**
*(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)*

- Aluminum Hat (Material Substitution), **Image 4.8-11**
    - Diecast to Near-Net Shape

      (Mass Savings even with increased material volume of 40-45%, Decreased Processing Time, Rapid and Increased Heat Dissipation)
    - Manufacturers and OEMs include: Chevrolet, Mercedes, Audi, BMW, Wilwood, Brembo, Motorcycles

**Image 4.8-11: Front Rotor Mass Reduced Component**
*(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)*

- Aluminum – Metal Matric Composite Disc (Material Substitution), **Image 4.8-12**
    - Sand Cast to Near-Net Shape
    - Manufacturers and OEMs include: GM, Ford, Chrysler, Toyota, Honda, Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Lotus, Wilwood, Brembo, Motorcycles

**Image 4.8-12: Front Rotor Mass Reduced Component**
*(Source: http://www.wilwood.com/Pdf/Catalogs/TechCatalog.pdf)*

- Cast Directional Cooling Fins Between Disc Surfaces, **Image 4.8-13**
  - Casting Process Change. Enhanced Disc Cooling.

    (Acts as Centrifuge Air Pump: Maximum Air Circulation for Increased Cooling. This is Required Due to Less Rotor Material Mass Available to Absorb Heat.)
  - Manufacturers and OEMs include: Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Wilwood, Brembo

**Image 4.8-13: Front Rotor Mass Reduced Component**
*(Source:http://www.highperformancepontiac.com/tech/hppp_1101_brake_rotor_guide/photo_03.html)*

- Disc Surface Cross-Drilling (**Image 4.8-14**)

- Improved Disc Cooling and Mass Savings

  (Disperse Built-Up Heat and Gases)

- Manufacturers and OEMs include: Chevrolet, Pontiac, Cadillac, Mercedes, Audi, BMW, Porsche, Ferrari, Lamborghini, Wilwood, Brembo, Motorcycles

**Image 4.8-14: Front Rotor Mass Reduced Component**
*(Source: http://www.pap-parts.com/products.asp?dept=2732)*

- Down-sizing Based on the Scaling Utilizing the 2006 Dodge RAM, **Image 4.8-15**
  - Ratio Vehicle Net Mass and Rotor Size versus Prius Specs (Lotus) to Reduce Rotor Size and Material Usage.

    (Mass Savings Due to Less Material Usage)

**Image 4.8-15: Front Rotor Size Normalization Mass Reduced Component**
*(Source: FEV, Inc.)*

The final front rotor assembly (**Image 4.8-16**) is the approximate design configuration based on the above combined ideas. This redesigned front rotor solution has a calculated mass of 5.60 kg. Although nearly all of these individual mass reduction ideas have been implemented by plenty of manufactures and OEMs individually, none have been utilized all at once in a single vehicle application. Therefore, the appropriate amount of industry testing and validation must be performed by any vehicle manufacturer in order to fit this design to a particular vehicle application. Concerns to be addressed would include the normal list of topics that are determined with any braking system. These would include some of the following requirements:

- Cracking and Deformation Resistance
- Degassing, Glazing and Debris Control
- Brake Pad Wear
- Cooling (Heat Dissipation) Performance
- Disc Heat Capacity versus Warping
- Quality and Geometric Tolerance:
  - Dimensioning, Surface Finish, Lateral Runout, Flatness, Perpendicularity and Parallelism
- Rotor Braking Surface Wear
- Rotor Life and Durability versus Warranty
- Braking Performance versus Component Longevity
- NVH Testing versus Functional Performance
- Rotor Assembly (Disc and Hat) Balancing

**Image 4.8-16: Front Rotor Mass Reduced Component Example**

*(Source: http://www.girodisc.com/Girodisc-Front-2-piece-rotors-for-Mazda-RX8_p_6346.html)*

#### 4.8.1.5.2 Splash Shields

The solution(s) chose to be implemented on the front splash shields (**Image 4.8-17**) was the combination of two individual brainstorming ideas. This redesigned Chevrolet Silverado Splash Shield solution has a calculated mass of 0.229 kg. These ideas included the following modifications to design, materials and processing:

- Plastic Glass-Filled, Ribbed and Webbed Shield (Material Substitution)
  - Injection Molded to Near-Net Shape and Combining Components (Mass Savings even with increased material volume of 200%, Component Simplification and Assembly Reduction)
- Down-sizing Based on the Scaling Utilizing the Ford F150
  - Ratio Vehicle Net Mass and Rotor Size versus Ford F150

**Image 4.8-17: Front Splash Shield Mass-Reduced Component Examples**
*(Source: FEV, Inc.)*

#### 4.8.1.5.3 Caliper Assembly

The redesigned Chevrolet Silverado front caliper assembly is still a multi-piece assembly comprised of the same components and design function. The caliper housing is now being made from cast magnesium and the assembly has a new reduced mass calculated to be 3.70 kg. The front caliper assembly (**Image 4.8-18** and **Image 4.8-19**) is still comprised of the same components and design function. These include: housing, mounting, mounting attachment bolts (2), inboard brake pad and shim plate, outboard brake pad and shim plate, pistons (2), piston seal ring (2), piston seal boots (2), mounting slide pins (2), mounting slide pin boots (2), housing bleeder valve, and housing bleeder valve cap.


**Image 4.8-18: Front Caliper Mass Reduced Assembly Example**
*(Source: http://www.speedhunters.com/wp-content/uploads/2010/03/GI-BNR34-154.jpg?random=1405437392167)*

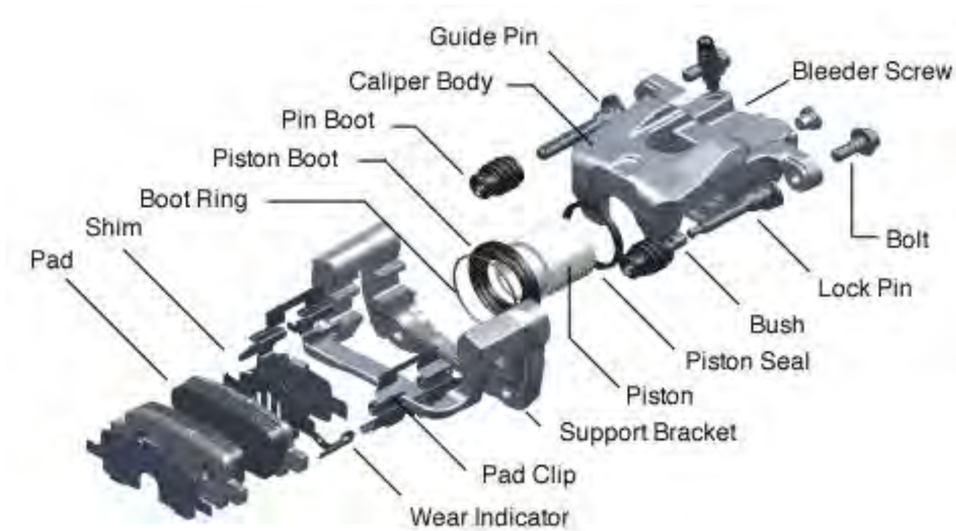



**Image 4.8-19: Front Caliper Assembly Component Diagram Example**
*(Source: http://www.brakewarehouse.com/)*

### 4.8.1.5.4 Housings

The front caliper housing (**Image 4.8-20**) has been mass reduced based on the 2002 Chevrolet Avalanche housing and the material has been changed from a cast iron design to a diecast magnesium design. Additional material volume of 70-80% was added to improve strength and increase mass surface to assist in the brake cooling function. This technology is not widely available and to some light airplane applications.


**Image 4.8-20: Front Caliper Housing Mass Reduced Component example**
*(Source:http://www.peterverdone.com/wiki/index.php?title=PVD_Land_Speed_Record_Bike#Caliper)*

While these alternatives are designed with the strength and performance required, they do add a significant cost while providing a large mass decrease. However, the weight savings achieved is quite substantial. This redesigned front caliper housing solution has a calculated mass of 1.60 kg. This mass decrease assists with reducing vehicle requirements for suspension loads, handling, ride quality, engine horsepower requirements, etc.

#### *4.8.1.5.4.1 Mountings*

The front caliper mounting (**Image 4.8-21**) has been mass reduced based on the Dodge Durango caliper bracket and the material was changed from cast iron to a die cast Magnesium design. While additional material volume of 70-80% was added to improve strength, the mass savings achieved was still significant. This redesigned front caliper mounting solution has a calculated mass of 0.692 kg.

**Image 4.8-21: Front Caliper Mounting Mass Reduced Component Example**
*(Source: http://www.gforcebuggies.com/Parts)*

The final front brake corner assembly (**Image 4.8-22**) is the approximate design configuration based on the above combined ideas. This redesigned Chevrolet Silverado front brake corner assembly solution has a calculated mass of 10.1 kg. Again, nearly all of these individual mass reduction ideas have been implemented by many manufactures and OEMs individually, but none have been utilized at once in a single vehicle application. Therefore, the appropriate amount of industry testing and validation must be performed by any vehicle manufacturer in order to fit this design to a particular vehicle application.


**Image 4.8-22: Front Brake System Mass Reduced Assembly Example**
*(Source: http://www.sharkwerks.com/products.php?pid=194)*

#### 4.8.1.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.8-6** shows the results of the mass reduction ideas that were evaluated for the Front Rotor/Drum and Shield Subsystem. This resulted in a subsystem overall mass savings of 22.0 kg and a cost increase differential of $47.00.

**Table 4.8-6: Mass Reduction and Cost Impact for the Front Rotor/Drum and Shield Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys/ Sub-Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 06 | 03 | 00 | Front Rotor/Drum and Shield Subsystem | | | | | | |
| 06 | 03 | 01 | Front Rotor and Shield | D | 12.61 | -$56.20 | -$4.46 | 29.3% | 0.51% |
| 06 | 03 | 02 | Front Caliper, Anchor and Attaching Components | A | 9.39 | $9.20 | $0.98 | 21.8% | 0.38% |
| | | | | C | 22.00 (Decrease) | -$47.00 (Increase) | -$2.14 (Increase) | 51.2% | 0.90% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.8.2 Rear Rotor / Drum and Shield Subsystem

#### 4.8.2.1 Subsystem Content Overview

**Image 4.8-23** represents the major brake components in the Rear Rotor/Drum and Shield Subsystem and their relative location and position to one another as on the vehicle rear corner.

**Image 4.8-23: Rear Rotor/Drum and Shield Subsystem Relative Location Diagram**
*(Source: A2MAC1)*

As seen in **Image 4.8-24**, the Rear Rotor/Drum and Shield Subsystem consists of the following major components: rear drum, rear backing plate, wheel cylinder, guide plate, and miscellaneous attaching components.

**Image 4.8-24: Rear Rotor / Drum and Shield Subsystem Current Major Components**
*(Source: FEV, Inc.)*

**Table 4.8-7** indicates the two sub-subsystems that make-up the Rear Rotor/Drum and Shield Subsystem. These are the Rear Drum Sub-subsystem and the Rear Drum Brake and Attaching Components Sub-subsystem. The most significant contributor to the mass within this subsystem was found to be within the Rear Drum Sub-subsystem (approximately 64.5%).

**Table 4.8-7: Mass Breakdown by Sub-subsystem for the Rear Rotor / Drum and Shield Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 06 | 04 | 00 | Rear Rotor/Drum and Shield Subsystem | |
| 06 | 04 | 07 | Rear Drum | 22.1 |
| 06 | 04 | 08 | Rear Drum Brake and Attaching Components | 12.2 |
| | | | Total Subsystem Mass = | 34.3 |
| | | | Total System Mass = | 101.0 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 33.9% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.40% |

#### 4.8.2.2 Chevrolet Silverado Baseline Subsystem Technology

As with the Front Brake subsystems previously discussed, the Chevrolet Silverado Rear Rotor/Drum and Shield Subsystem (**Image 4.8-25**) follows typical industry standards. The drums (**Image 4.8-26**) are a single-piece design cast out of grey iron and manufactured to SAE specifications. The backing plate assembly (**Image 4.8-27**) is composed of several components. These include: the backing plate (**Image 4.8-28**), which is a stamped steel construction; and the wheel cylinder assembly (**Image 4.8-29**), also composed of several components. The guide plate (**Image 4.8-30**) is a stamped steel component. The spacer block (**Image 4.8-31**) is stamped from a heavy thick steel plate. The rivets (**Image 4.8-32**) are drawn from steel rod. The brake pads (**Image 4.8-33**) are of standard construction with steel backing plates and friction pad materials. And, the actuation lever (**Image 4.8-34**) is a stamped steel component. The current OEM Chevrolet Silverado rear brake corner assembly has a mass of 17.1 kg.

**Image 4.8-25: Rear Brake System Assembly Example**
*(Source: A2MAC1)*

### 4.8.2.3 Mass Reduction Industry Trends

The hydraulic drum brake system has been used in the automotive industry since the 1930's. The drum brake system's primary parts are the drum, backing plate, wheel cylinder, and brake shoes. Standard automotive brake drums and wheel cylinders are usually sand casted from iron. The backing plate is typically stamped from thick low carbon steel. Over the years, the disc brake system has replaced the drum brake system on the front wheels.

There have been relatively little advancements made to the drum brake system as far as light weighting is concerned. The most popular changes have been not so much in design, but in material. On a limited scale, the drum, wheel cylinder, and backing plate are now made out of aluminum.

#### 4.8.2.3.1 Drums

The baseline OEM Chevrolet Silverado rear drum (**Image 4.8-26**) is a single piece design cast out of grey iron and has a mass of 11.0 kg.

**Image 4.8-26: Rear Drum Current Component**
*(Source: FEV, Inc.)*

A drum brake system uses brake shoes with friction material attached to them. The shoes are pushed, by the wheel cylinder, against the drum. This causes friction, which slows or stops the vehicle.

Drum rotation causes the shoes to press against the drum with more force than with disc brakes. However, since the shoes are enclosed and not exposed to air flow, it cannot dissipate heat into the atmosphere as effectively as a disk brake system.

#### 4.8.2.3.2 Backing Plate Assembly

The baseline OEM Chevrolet Silverado rear backing plate assembly is a multi-piece assembly with the major components being made of cast iron and stamped steel construction and has a mass of 3.75 kg. Traditionally, backing plate assemblies (**Image 4.8-27**) are comprised of several components. These include: backing plate, guide plate, guide plate spacer, rivets, wheel cylinder assembly, and mounting bolts.

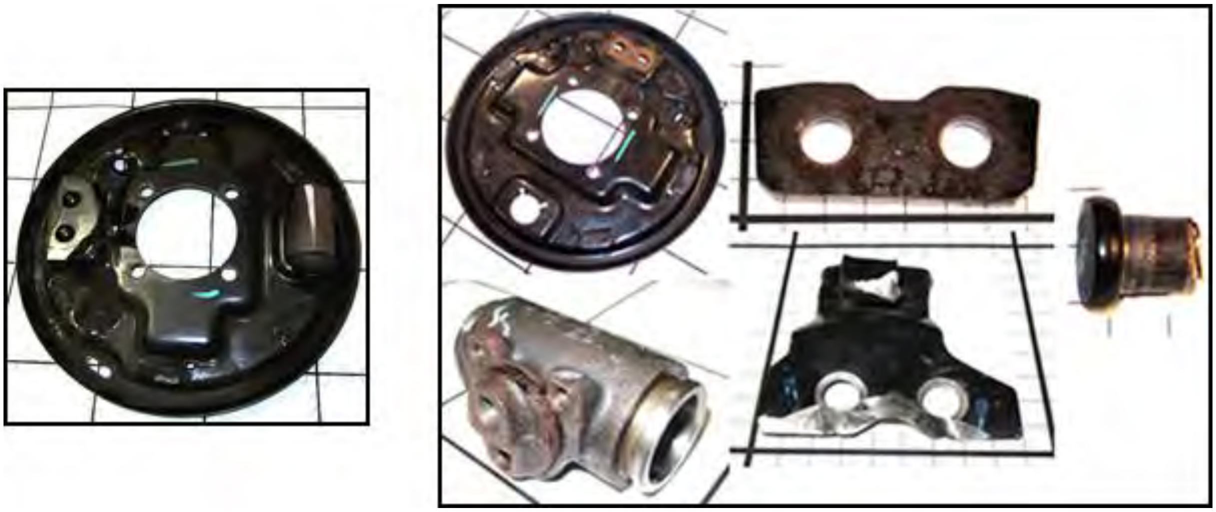


**Image 4.8-27: Rear Backing Plate Assembly Current Components**
*(Source: FEV, Inc.)*

### *4.8.2.3.2.1 Backing Plate*

The baseline OEM Chevrolet Silverado backing plate is a single piece stamped steel design and has a mass of 2.89 kg. A majority of backing plates (or dust shields) (**Image 4.8-28**) are made from stamped, light gage steel. Some are vented or slotted for reduced material usage and increased weight savings. Alternative materials are now beginning to be examined for use to further reduce weight contribution. These include aluminum, high strength steels, and even various reinforced plastics.

**Image 4.8-28: Rear Backing Plate Current Component**
*(Source: FEV, Inc.)*

While these alternatives now are designed with the strength and performance required they do add a significant cost-versus-mass increase. However, the weight savings achieved is quite substantial and assists with reducing such vehicle requirements for suspension loads, handling, ride quality, and engine horsepower requirements. Other advanced development includes using bulk molding compound using long randomly oriented carbon fiber continues to be of interest due to the ability to easily mold it into complex shapes. However, temperature extremes encountered by brake components and the current cost of the material will be serious challenges for some time to come.

#### *4.8.2.3.2.2 Wheel Cylinder Housing*

The baseline OEM Chevrolet Silverado rear wheel cylinder housing is a single piece cast iron design and has a mass of 0.458 kg. Wheel cylinder housings (**Image 4.8-29**) have normally been made from various grades of cast iron for adequate strength and function. Now with advances in materials and processing methods other choices are available and being utilized in aftermarket and high performance applications as well as OEM vehicle markets. Among some of these alternate mediums are aluminum, titanium, steel, and magnesium. Forming and fabrication methods include casting and billet machining.

**Image 4.8-29: Rear Wheel Cylinder Housing Current Component**
*(Source: FEV, Inc.)*

#### *4.8.2.3.2.3 Guide Plate*

The baseline OEM Chevrolet Silverado rear guide plate is a single piece stamped steel design and has a mass of 0.073 kg. The guide plate (**Image 4.8-30**) is made from stamped, light gage steel. Alternative materials are now beginning to be examined for use to further reduce weight contribution. These include aluminum, high-strength steels, and even various reinforced plastics.

**Image 4.8-30: Rear Guide Plate Current Component**
*(Source: FEV, Inc.)*

### *4.8.2.3.2.4 Spacer Block*

The baseline OEM Chevrolet Silverado rear guide plate spacer block is a single piece stamped steel design and has a mass of 0.099 kg. The spacer block (**Image 4.8-31**) is made from stamped, heavy gage steel. Alternative materials are now beginning to be examined for use to further reduce weight contribution. These include aluminum, high-strength steels, and even various reinforced plastics.

**Image 4.8-31: Rear Guide Plate Spacer Block Current Component**
*(Source: FEV, Inc.)*

#### *4.8.2.3.2.5 Guide Plate Rivet*

The baseline OEM Chevrolet Silverado rear guide plate rivet is a single piece drawn steel design and has a mass of 0.034 kg. The rivets (**Image 4.8-32**) are made from forged heavy gage steel. Alternative materials are now beginning to be examined for use to further reduce weight contribution. These include aluminum, high-strength steels, and even various reinforced plastics.

**Image 4.8-32: Rear Guide Plate Rivet Current Component**
*(Source: FEV, Inc.)*

#### 4.8.2.3.3 Brake Pads

The baseline OEM Chevrolet Silverado rear drum brake pads are of standard construction with steel backing plates and friction pad materials. They have a mass of 1.58 kg. The brake pads (**Image 4.8-33**) had had little change in design, materials or processing in recent years. Most have steel backing plates with a molded friction material attached to them. Various sized braking surfaces and molded shapes are common variations across different vehicle platforms. Most material differences are focused only in the friction material going from traditional asbestos now to semi-metallic and full metallic as well as various ceramic compounds. While these friction materials greatly affect performance and vehicle stopping distances under various conditions, little is accomplished in saving mass and reducing material weight.

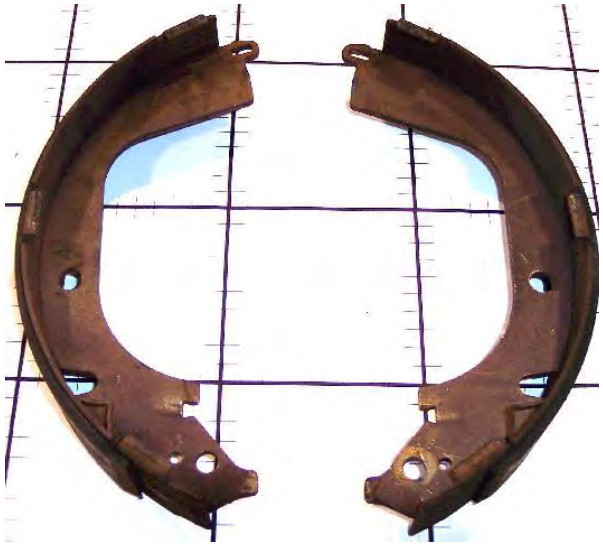


**Image 4.8-33: Rear Drum Brake Pad Current Components**
*(Source: FEV, Inc.)*

### 4.8.2.3.4 Actuation Lever

The baseline OEM Chevrolet Silverado parking brake actuation lever is a standard construction of a stamped steel design with a mass of 0.303 kg. The actuation lever (**Image 4.8-34**) has had little change in design, materials or processing in recent years.

**Image 4.8-34: Actuation Lever Current Components**
*(Source: FEV, Inc.)*

#### 4.8.2.4 Summary of Mass Reduction Concepts Considered

**Table 4.8-8** shows the mass reduction ideas considered from brainstorming activity for the Rear Rotor/Drum and Shield Subsystem and its various components. These ideas include part modifications, material substitutions, processing and fabrication differences, and use of alternative parts currently in production and used on other vehicles and applications.

**Table 4.8-8: Summary of Mass Reduction Concepts Initially Considered for the Rear Rotor / Drum and Shield Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Rear Rotor/Drum and Shield Subsystem** | | | |
| Drum | Vent (slot) rear drums (Circumference braking surface) (27) | ~1% wt save | Low Risk - ~5% cost increase |
| | Cross-Drill rear drums (Circumference braking surface) (28) | ~5% wt save | Low Risk - ~5% cost increase |
| | Change Material for Drum - Al/MMC (29) | ~60% wt save | ~2x cost increase |
| | Add fins around Drum OD to allow thinner material while still dissipating/absorbing heat (30) | ~2% wt save | Low Risk - ~2% cost save |
| | Clearance drill holes in Drum top hat surface to reduce wt (31) | ~2% wt save | Low Risk - ~5% cost increase |
| | Replace from comparable A2MAC1 database (32) | 0 wt save | 0 cost change |
| | Combine 28 & 31 | ~5% wt save | Low Risk - ~5% cost save |
| | Combine 27, 28, 29, 30, 31 & 32 | ~60% wt save | ~2x cost save |
| | Combine 27, 28, 30 & 31 | ~5% wt save | Low Risk - ~5% cost increase |
| | | | |
| Backing Plate | Vent Backing Plate with slots (33) | ~1% wt save | Low Risk - ~1% cost save |
| | Make out of plastic (34) | ~5% wt save | ~2x cost increase |
| | Make out of High Strength Steel (35) | ~5% wt save | ~2.5x cost increase |
| | Make out of Aluminum (36) | ~50% wt save | ~80% cost increase |
| | Make out of Titanium (37) | ~30% wt save | ~7x cost increase |
| | Tailor Rolled Blank to reduce thickness (38) | ~5% wt save | ~5% cost increase |
| | Replace from comparable A2MAC1 database (39) | 0 wt save | 0 cost change |
| | Combine 33 & 36 | ~50% wt save | ~70% cost increase |
| | | | |
| Guide Plate | Make Guide Plate out of stamped Aluminum (40) | ~50% wt save | ~60% cost increase |
| | Stamp Guide Plate from Backing Plate Mtl - Eliminates Guide Plate, Spacer & Rivets (46) | ~2x wt save | ~2x cost save |
| | Single Layer Weld New Guide Plate to Backing Plate to eliminate Spacer & Rivets (45) | ~120% wt save | ~40% cost save |
| | Redesign Guide Plate offset to eliminate Spacer & Shorter Rivets (47) | ~150% wt save | ~1.25x cost save |
| | | | |
| Guide Plate Spacer | Make Spacer out of Aluminum (41) | ~50% wt save | ~60% cost increase |
| | Make Spacer out of Plastic (43) | ~50% wt save | ~70% cost increase |
| | | | |
| Guide Plate Rivets | Make Rivets out of Aluminum (42) | ~40% wt save | ~40% cost increase |
| | Mutli Layer Weld Guide Plate & Spacer to Backing Plate to eliminate Rivets (44) | ~2x wt save | ~100% cost save |
| | Combine 40, 41 & 42 | ~50% wt save | ~60% cost increase |
| | Combine 40, 42 & 47 | ~300% wt save | ~800% cost save |

**Table 4.8-8 continued next page**

**Table 4.8-8 (Cont'd)**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Rear Rotor/Drum and Shield Subsystem** | | | |
| Brake Shoes | Replace from comparable A2MAC1 database (48) | 0 wt save | 0 cost change |
| | Make brake shoe wear material thinner (49) | ~5% wt save | ~5% cost save |
| Actuation Lever | Make out of HSS (50) | ~2% wt save | ~3x cost increase |
| | Make out of Titanium (51) | ~70% wt save | ~7x cost increase |
| | Make out of Forged Aluminum (52) | ~50% wt save | ~100% cost increase |
| Wheel Cylinder | Make Wheel Cylinder out of Forged Aluminum (53) | ~50% wt save | ~60% cost increase |

### 4.8.2.5 Selection of Mass Reduction Ideas

**Table 4.8-9** shows the mass reduction ideas for the Rear Rotor/Drum and Shield Subsystem that were selected for detailed evaluation of both the mass savings achieved and the cost to manufacture. Several ideas suggest aluminum and aluminum metal matrix as alternate materials.

**Table 4.8-9: Mass Reduction Ideas Selected for the Rear Rotor/Drum and Shield Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|---|---|---|
| **06** | **04** | **00** | **Rear Rotor/Drum and Shield Subsystem** | |
| 06 | 04 | 00 | Drum | Change drum material to Al/MMC |
| | | | | Downsizing based on fins added to hat |
| | | | | |
| 06 | 04 | 00 | Backing Plate | Make out of cast aluminum |
| | | | | |
| 06 | 04 | 00 | Guide Plate | Stamp from backing plate material |
| | | | | |
| 06 | 04 | 00 | Guide Plate Spacer | Eliminate with backing material |
| | | | | |
| 06 | 04 | 00 | Backing Plate Rivets | Eliminate with backing material |
| | | | | |
| 06 | 04 | 00 | Wheel Cylinder Housing | Make out of forged aluminum |
| | | | | |
| 06 | 04 | 00 | Actuation Lever | Make out of forged aluminum |

#### 4.8.2.5.1 Drums

The solution(s) chosen to be implemented on the final rear drum (**Image 4.8-35**) was the combination of multiple individual brainstorming ideas. These ideas included the following modifications to component design, material utilized and processing methods required:

- Make out of aluminum metal matrix
  - Die cast to near-net shape

    (Mass savings even with increased material volume of 20-30%, increased processing time, rapid and increased heat dissipation)

**Image 4.8-35: Rear Rotor Mass Reduced Component**
*(Source: http://www.sae.org/mags/tbe/CHASS/9417)*

- Add Cooling Fins, **Image 4.8-36**
  - Die cast to net shape

**Image 4.8-36: Rear Rotor Mass Reduced Component (with Cooling Fins)**
*(Source: http://www.compositesworld.com/articles/metal-matrix-composites-used-to-lighten-military-brake-drums)*

The redesigned Chevrolet Silverado rear drum solution has a calculated mass of 4.20 kg. Although nearly all of these individual mass reduction ideas have been implemented by many manufactures and OEMs individually, none have been utilized all at once in a single vehicle application. Therefore the appropriate amount of industry testing and validation must be performed by any vehicle manufacturer in order to fit this design to a particular vehicle application. Concerns to be addressed include the normal list of topics determined with any braking system. These would include some of the following requirements:

- Cracking and deformation resistance
- Degassing, glazing, and debris control
- Brake pad wear
- Cooling (heat dissipation) performance
- Drum heat capacity versus warping
- Quality and geometric tolerance:
    - Dimensioning, surface finish, lateral runout, flatness, perpendicularity, and parallelism
- Drum braking surface wear
- Drum life and durability versus warranty
- Braking performance versus component longevity

- NVH testing versus functional performance
- Drum balancing

#### 4.8.2.5.2 Backing Plate

The solution chosen to be implemented on the rear backing plate (**Image 4.8-37**) was the combination of three individual brainstorming ideas. This redesigned Chevrolet Silverado rear backing plate solution has a calculated mass of 2.19 kg. These ideas included the following design, materials and processing modifications:

- Cast aluminum fabrication (material substitution)
  - One piece casting design combining components (mass savings even with increased material volume of 120-130%, component simplification and assembly reduction)
- Cast-in guide plate
  - Eliminates guide plate, guide plate spacer, and guide plate rivets

**Image 4.8-37: Casted Rear Backing Plate Mass Reduced Component Example**
*(Source: http://www.macsmotorcitygarage.com/2014/04/29/another-look-at-smokey-yunicks-capsule-car/)*

#### 4.8.2.5.3 Wheel Cylinder Housing

The redesigned Chevrolet Silverado wheel cylinder housing (**Image 4.8-38**) is now forged out of aluminum and has a new reduced mass calculated to be 1.41 kg (Mass savings even with increased material volume of 35-40%). This technology is available and being utilized in aftermarket and high performance applications as well as a few OEM vehicle markets. Some manufacturers and vehicle applications include the Citroën

Elysée 1.6 SX (2007), Dacia Lodgy 1.5 DCi Laureate (2013), Fiat Grande Punto 1.2 Dynamic (2006), Honda Civic 1.8 LX (2007), Lancia Ypsilon 0.9 Twin Air Platinum (2012), Opel Corsa 1.3 CDTi Cosmo (2007), and Toyota Prius 1.5 Base (2008).

**Image 4.8-38: Wheel Cylinder Housing Mass Reduced Assembly Example**
*(Source: http://brakeperformance.com/wheel-cylinders/wheel-cylinders-rebuild-kit.php)*

### 4.8.2.5.4 Actuation Lever

The actuation lever (**Image 4.8-39**) was changed from stamped steel to a stamped aluminum design. While additional material volume of 45-55% was added to improve strength, the mass savings achieved was still significant. This redesigned Chevrolet Silverado actuation lever solution has a calculated mass of 0.168 kg.

**Image 4.8-39: Actuation lever Mass Reduced Component Example**
*(Source: http://www.mytransasia.com/en/products_show.asp?showid=254&product=4241.72)*

The final rear brake corner assembly (**Image 4.8-40**) is the approximate design configuration based on the above combined ideas. This redesigned Chevrolet Silverado rear brake corner assembly solution has a calculated mass of 8.97 kg. To reiterate, nearly all of these individual mass reduction ideas have been implemented by plenty of manufactures and OEMs individually, but none have been utilized all at once in a single vehicle application. Therefore the appropriate amount of industry testing and validation must be performed by any vehicle manufacturer in order to fit this design to a particular vehicle application.

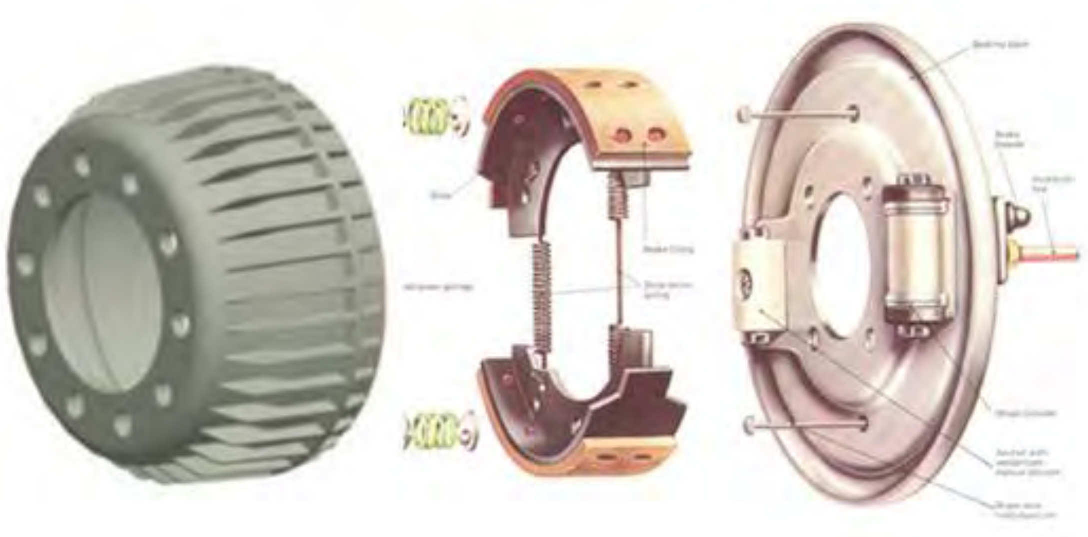


**Image 4.8-40: Rear Brake System Mass Reduced Assembly Example**
*(Source: FEV, Inc.)*

#### 4.8.2.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.8-10** shows the results of the mass reduction ideas that were evaluated for the Rear Rotor/Drum and Shield Subsystem. This resulted in a subsystem overall mass savings of 16.3 kg and a cost increase differential of $71.02.

**Table 4.8-10: Mass Reduction and Cost Impact for the Rear Rotor/Drum and Shield Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Ideas: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys/ Sub-Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 06 | 04 | 00 | Rear Rotor/Drum and Shield Subsystem | | | | | | |
| 06 | 04 | 07 | Rear Drum | D | 13.7 | -$77.34 | -$5.65 | 40.0% | 0.56% |
| 06 | 04 | 08 | Rear Drum Brake and Attaching Components | A | 2.62 | $6.33 | $2.42 | 7.64% | 0.11% |
| | | | | D | 16.31 (Decrease) | -$71.02 (Increase) | -$4.35 (Increase) | 47.6% | 0.66% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.8.3 Parking Brake and Actuation Subsystem

#### 4.8.3.1 Subsystem Content Overview

**Image 4.8-41** represents the major parking brake components in the Parking Brake and Actuation Subsystem, which includes: the parking brake pedal actuator sub-assembly and the actuation cable assemblies with guides and brackets that are located on the vehicle from the engine firewall (front of vehicle) all the way to the rear wheels.

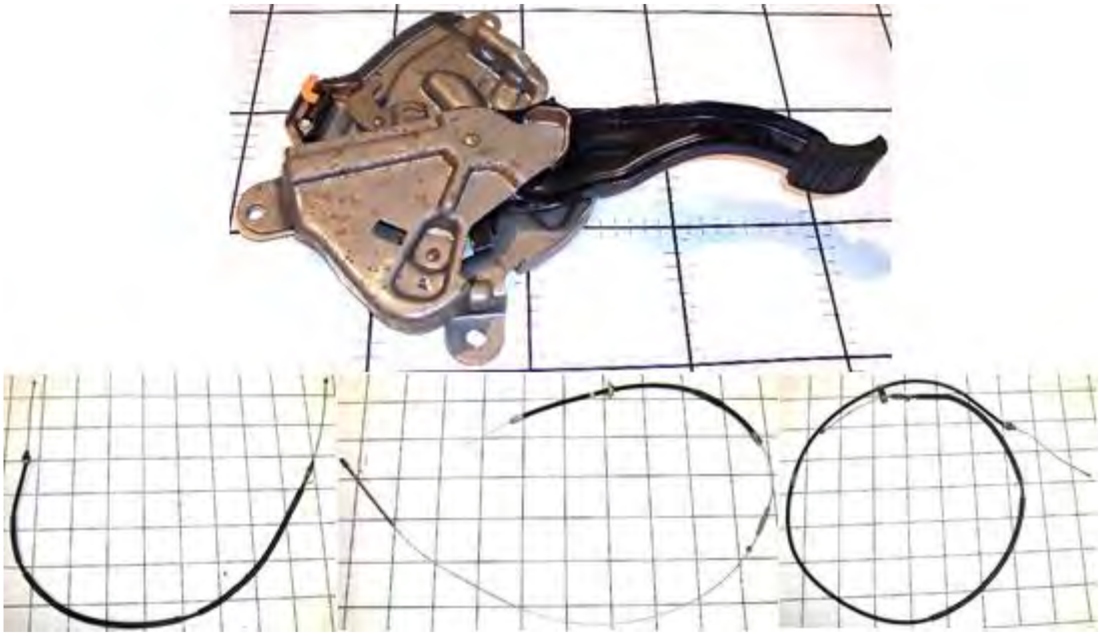


**Image 4.8-41: Parking Brake and Actuation Subsystem Current Sub-assemblies**
*(Source: FEV, Inc.)*

The Parking Brake and Actuation Subsystem (**Table 4.8-11**) consists of the parking brake controls and the parking brake cables and attaching components. The most significant contributor to mass is the parking brake cables and attaching components (approximately 58.1%) followed by the parking brake controls (approximately 41.9%).

**Table 4.8-11: Mass Breakdown by Sub-subsystem for the Parking Brake and Actuation Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 06 | 05 | 00 | Parking Brake and Actuation Subsystem | |
| 06 | 05 | 01 | Parking Brake Controls | 1.97 |
| 06 | 05 | 02 | Parking Brake Cables and Attaching Components | 2.73 |
| | | | Total Subsystem Mass = | 4.70 |
| | | | Total System Mass = | 101.0 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 4.66% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.19% |

### 4.8.3.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado Parking Brake Subsystem (**Figure 4.8-3**) follows typical industry standards. The Silverado uses a cable-operated rear parking brake system. The system consists of a foot operated lever which pulls on the parking brake cables causing both of the rear brake shoes to engage the rear brake drums. The mass of this entire Parking Brake and Actuation Subsystem is 4.70 kg.

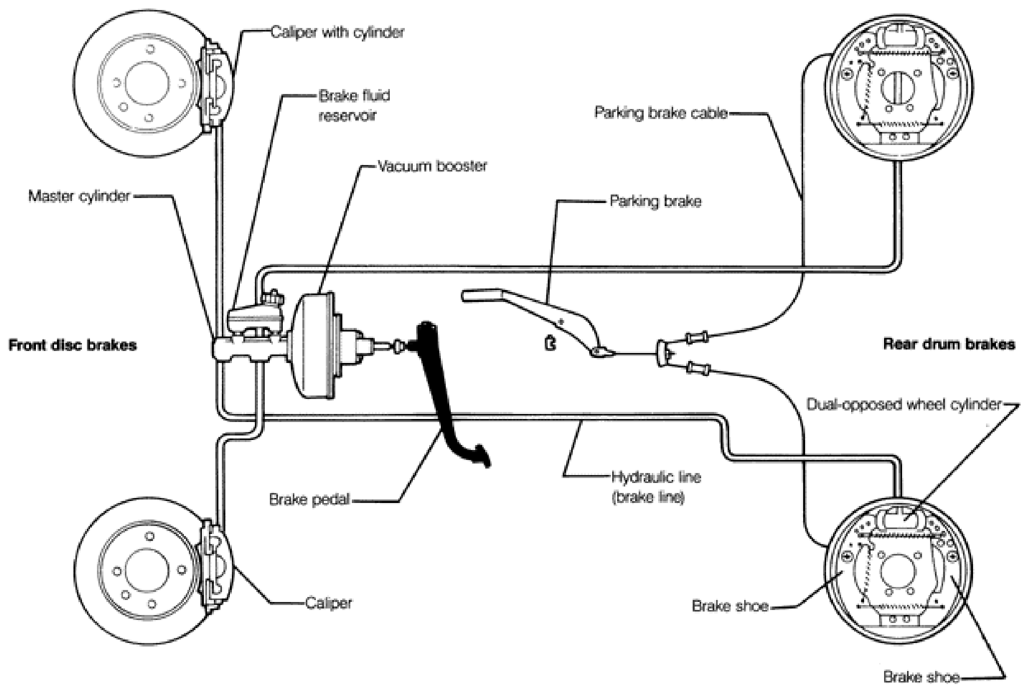



**Figure 4.8-3: Parking Brake and Actuation Subsystem Layout and Configuration**
*(Source: http://www.bing.com/images/search?q=Silverado+front+disc+Brake+system&id)*

### 4.8.3.3 Mass Reduction Industry Trends

Alternatives to cable-operated parking brake systems are focused on hydraulic, electrical, and electro-mechanical components to actuate the parking brake system at the rear wheels. The use of push-button switches and console touch screens can eliminate the need for hand levers or foot pedals in the cabin interior. Electrical wiring and actuators can provide input controls to initiate the clamping force at the rear wheels. This allows the reduction (if not the elimination) in the length and number of cable assemblies routed under and along the vehicle floor pan and sub-frame structures.

TRW offers a front and rear wheel electric park brake system (**Image 4.8-42**) that provides four-wheel park brake capability with associated claims of improved safety. Volkswagen has utilized an electro-hydraulic park brake system (**Image 4.8-43**) that is initiated by an electric motor that drives a geared actuator providing direct hydraulic pressure influence by pushing directly on the caliper piston inside the caliper housing. Other designs offer a compromise of a hybrid approach, still using electronic actuation and motor-driven systems but integrating them into the existing rear cable systems already present on most vehicles (**Image 4.8-44**).

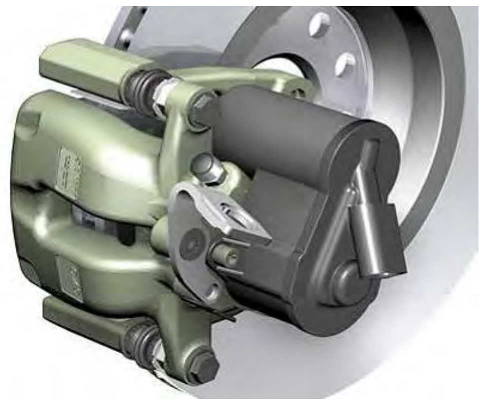



**Image 4.8-42 (Left): TRW Park Brake System**
*(Source: http://www.buzzbox.com/news/2010-09-29/gas:technology/?clusterId=2019488)*

**Image 4.8-43 (Right): Volkswagen Park Brake System**
*(Source: http://www.volkspage.net/technik/ssp/ssp/SSP_346.pdf)*

**Image 4.8-44: Kuester Park Brake System**
*(http://www.kuester.net/pdf/Sonderdruck_engl.pdf)*

#### 4.8.3.3.1 Parking Brake Pedal Frame and Arm Sub-Assembly

The baseline OEM Chevrolet Silverado parking brake pedal frame and arm sub-assembly (**Image 4.8-45**) is a multi-piece design of stamped steel fabrication welded into a sub-assembly comprised of several components, including: mounting plate assembly, return spring, parking brake lever assembly, ratchet paw, ratchet return spring and cover plate. This overall sub-assembly has a mass of 1.95 kg.

Many high-performance and luxury vehicle models have begun utilizing alternate materials and designs in order to improve mass and expense. Another option being implemented by many OEMs is to use electronics and button actuators in order to engage the parking brake system. This allows for a complete elimination of pedal and hand lever sub-assemblies for vehicle cab interiors, maximizing mass savings. This electronic actuation configuration was also mentioned in the March 2010 Lotus Report.

**Image 4.8-45: Parking Brake Pedal Frame Current Sub-assembly**
*(Source: FEV, Inc.)*

#### *4.8.3.3.1.1 Mounting Plate*

The baseline OEM Chevrolet Silverado mounting plate is a single piece stamped steel design and has a mass of 0.766 kg. The mounting plate (**Image 4.8-46**) is made from stamped, light gage steel. Alternative materials being examined for use to further reduce weight contribution include aluminum, high strength steels, and reinforced plastics.

**Image 4.8-46: Mounting Plate Current Component**
*(Source: FEV, Inc.)*

#### *4.8.3.3.1.2 Parking Brake Lever*

The baseline OEM Chevrolet Silverado parking brake lever is of a stamped steel design and has a mass of 0.442 kg. The Parking Brake Lever (**Image 4.8-47**) is made from stamped, light gage steel. Alternative materials being examined for use to further reduce weight include aluminum, high strength steels, and reinforced plastics.

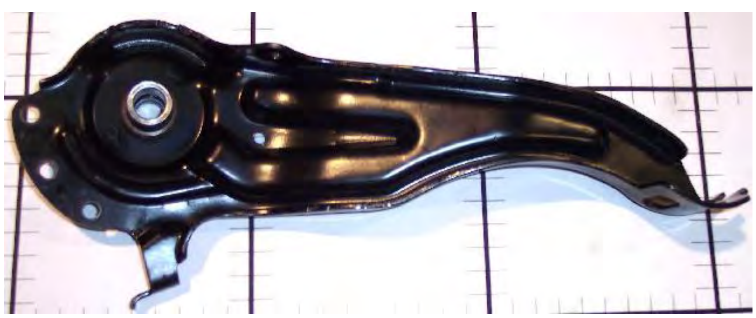


**Image 4.8-47: Parking Brake Lever Current Component**
*(Source: FEV, Inc.)*

#### *4.8.3.3.1.3 Cover Plate*

The baseline OEM Chevrolet Silverado cover plate is a single piece stamped steel design and has a mass of 0.405 kg. The cover plate (**Image 4.8-48**) is made from stamped, light gage steel. Alternative materials being examined for use to further reduce weight contribution include aluminum, high-strength steels, and reinforced plastics.

**Image 4.8-48: Cover Plate Current Component**
*(Source: FEV, Inc.)*

4.8.3.3.2 Cable System Sub-Assembly

The baseline OEM Chevrolet Silverado cable assemblies (**Image 4.8-49**) are multi-piece designs of wound steel and sleeved poly shields into sub-assemblies with brackets and fasteners added. This sub-subsystem has a mass of 2.73 kg. Many high-performance and luxury vehicle models utilize alternate cable configurations with hand lever actuators located in the center console between the front seats. This allows for a shorter path to the rear parking brakes, therefore requiring less cable length (and weight).

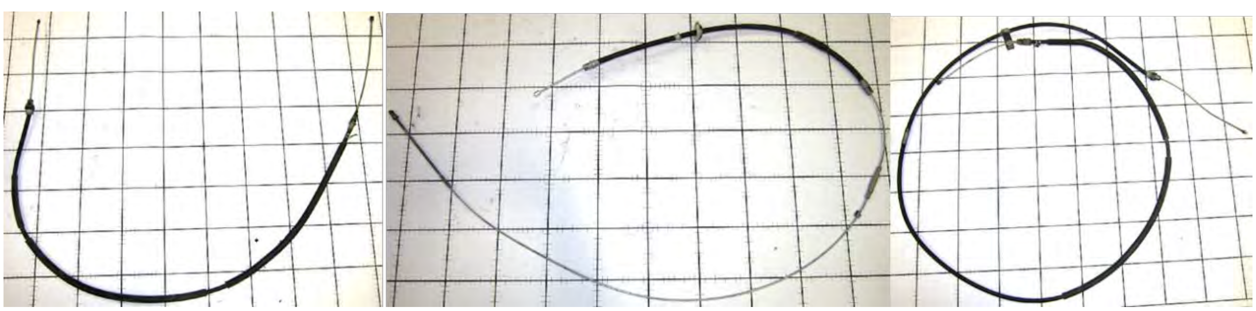


**Image 4.8-49: Cable System Current Sub-assemblies**
*(Source: FEV, Inc.)*

#### 4.8.3.4 Summary of Mass Reduction Concepts Considered

**Table 4.8-12** shows mass reduction ideas from our brainstorming activity for the Parking Brake and Actuation Subsystem. Ideas include material substitutions and use of parts currently in production on other vehicles.

**Table 4.8-12: Summary of Mass Reduction Concepts Initially Considered for the Parking Brake and Actuation Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Parking Brake and Actuation Subsystem** | | | |
| Parking Brake Lever & Frame | Make parking brake lever & frame out of hss (55) | ~2% wt save | Low risk - ~3x cost increase |
| | Make parking brake lever & frame out of aluminum (56) | ~50% wt save | Low risk - ~80% cost increase |
| | Make parking brake lever & frame out of magnesium (57) | ~60% wt save | Racing/aftermarket- ~80% cost increase |
| | Make parking brake lever & frame out of plastic composite (PA6 GF30) (58) | ~60% wt save | Low risk - ~3x cost increase |
| | Make parking brake lever & frame out of titanium (59) | ~30% wt save | Low risk - ~7x cost increase |
| | | | |
| Parking Brake Cables | Make out of synthetic cable | ~30% wt save | ~50% cost increase |

#### 4.8.3.5 Selection of Mass Reduction Ideas

**Table 4.8-13** shows one mass reduction idea for the Parking Brake and Actuation Subsystem that we selected for detail evaluation.

**Table 4.8-13: Mass Reduction Idea Selected for the Detailed Parking Brake and Actuation Subsystem Analysis**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|---|---|---|
| **06** | **05** | **00** | **Parking Brake and Actuation Subsystem** | |
| 06 | 05 | 00 | Park Brake Lever & Frame | Make parking brake lever & frame out of Magnesium |
| 06 | 05 | 00 | Parking Brake Cables | Make out of synthetic cable |

The chosen solution to implement for this study was to make these stamped steel components (mounting plate, parking brake lever, and the cover plate) out of cast magnesium and to make the parking brake cables out of a synthetic cable. The mass reduced redesign of this entire Parking Brake and Actuator Sub-subsystem is now reduced to 3.25 kg.

#### 4.8.3.5.1 Parking Brake Pedal Frame and Arm Assembly

The three main components of the parking brake pedal frame and arm assembly were changed from stamped steel construction to cast magnesium. The new mass reduced mounting plate (**Image 4.8-50**), parking brake lever (**Image 4.8-51**), and cover plate (**Image 4.8-52**) are pictured. This redesigned Chevrolet Silverado parking brake pedal frame and arm assembly has a new calculated mass of 1.95 kg.

##### *4.8.3.5.1.1 Mounting Plate*

The mounting plate is now casted out of magnesium. The new mounting plate has a net mass of 0.323 kg.

**Image 4.8-50: Mounting Plate Mass Reduced Component**
*(Source: FEV, Inc.)*

##### *4.8.3.5.1.2 Parking Brake Lever*

The parking lever is now cast out of magnesium. This new parking brake lever has a net mass of 0.186 kg.

**Image 4.8-51: Parking Brake Lever Mass Reduced Component**
*(Source: FEV, Inc.)*

#### *4.8.3.5.1.3 Cover Plate*

The cover plate is now cast out of magnesium. This new cover plate has a net mass of 0.171 kg.

**Image 4.8-52: Cover Plate Mass Reduced Component**
*(Source: FEV, Inc.)*

#### 4.8.3.5.2 Parking Brake Cables

The three parking brake cables were changed from braided steel construction to braided synthetic cable. The new mass reduced front cable (**Image 4.8-53**), rear axle cable, LH (**Image 4.8-54**), and rear axle cable, RH (**Image 4.8-55**) are pictured subsequently.

The redesigned Chevrolet Silverado parking brake cables have a new total calculated mass of 1.21 kg versus the baseline mass of 1.73 kg.

#### *4.8.3.5.2.1 Front Cable*

The front cable is now made out of a woven synthetic cable. This new front cable has a new mass of 0.307 kg versus the baseline mass of 0.439 kg.

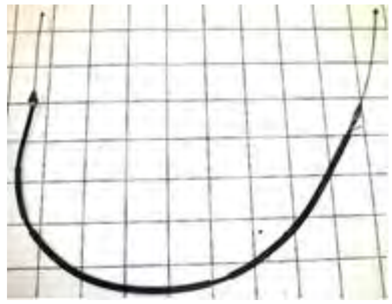


**Image 4.8-53: Front Cable Mass Reduced Component**
*(Source: FEV, Inc.)*

#### *4.8.3.5.2.2 Rear Axle Cable, LH*

The rear axle cable, LH is now made out of a woven synthetic cable. This new rear axle cable, LH has a new mass of 0.332 kg versus the baseline mass of 0.474 kg.

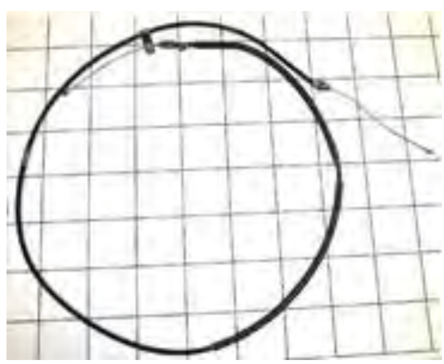


**Image 4.8-54: Rear Axle Cable, LH Mass Reduced Component**
*(Source: FEV, Inc.)*

#### *4.8.3.5.2.3 Rear Axle Cable, RH*

The rear axle cable, RH is now made out of a woven synthetic cable (**Image 4.8-55**). This new rear axle cable, RH has a new mass of 0.571 kg versus the baseline mass of 0.816 kg.

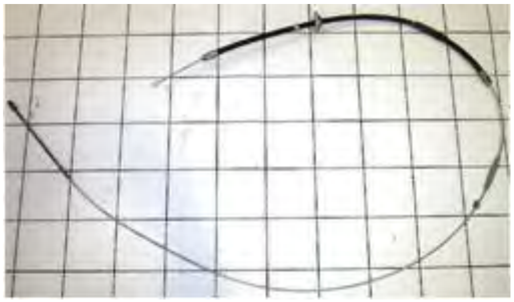


**Image 4.8-55: Rear Axle Cable, RH Mass Reduced Component**
*(Source: FEV, Inc.)*

#### 4.8.3.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.8-14** shows the results of the mass reduction ideas evaluated for the Parking Brake and Actuation Subsystem. This resulted in a subsystem overall mass savings of 1.45 kg and a cost increase differential of $15.56.

**Table 4.8-14: Mass Reductions and Cost Impact for the Parking Brake and Actuation Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Ideas: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys/ Sub-Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 06 | 05 | 00 | Parking Brake and Actuation Subsystem | | | | | | |
| 06 | 05 | 01 | Parking Brake Controls | D | 0.93 | $0.14 | $0.15 | 19.8% | 0.04% |
| 06 | 05 | 02 | Parking Brake Cables and Attaching Components | X | 0.52 | -$15.70 | -$30.28 | 11.0% | 0.02% |
| | | | | X | 1.45 (Decrease) | -$15.56 (Increase) | -$10.72 (Increase) | 30.9% | 0.06% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.8.4 Brake Actuation Subsystem

#### 4.8.4.1 Subsystem Content Overview

**Image 4.8-56** represents the major sub-assemblies components in the Brake Actuation Subsystem. These include the brake pedal actuator sub-assembly, the accelerator pedal actuator sub-assembly, master cylinder, master cylinder reservoir and various brake lines, hoses, and associated brackets and fasteners located on the vehicle that run to each brake corner assembly at each wheel.

**Image 4.8-56: Brake Actuation Subsystem Major Components and Sub-assemblies**
*(Source: FEV, Inc.)*

As seen in **Table 4.8-15**, the Brake Actuation Subsystem consists of the master cylinder and reservoir, actuator assemblies (brake and accelerator), and the brake lines and hoses. The most significant contributors to the mass are the actuator assemblies (approximately 71.1%) followed by the brake lines and hoses (approximately 18.9%).

**Table 4.8-15: Mass Breakdown by Sub-subsystem for the Brake Actuation Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 06 | 06 | 00 | Brake Actuation Subsystem | |
| 06 | 06 | 01 | Master Cylinder and Reservoir | 1.07 |
| 06 | 06 | 02 | Actuator Assemblies | 7.58 |
| 06 | 06 | 03 | Brake Lines and Hoses | 2.02 |
| | | | Total Subsystem Mass = | 10.66 |
| | | | Total System Mass = | 101.0 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 10.6% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.43% |

#### 4.8.4.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado's Brake Actuation Subsystem follows typical industry standards. The Silverado uses a typical multi-zone master cylinder (**Image 4.8-57**) with conventional ABS controls and steel tubing (**Image 4.8-58**) to each of the wheel brake systems. The brake pedal actuator sub-assembly (**Image 4.8-59**) is made of conventional stamped steel construction with welded assembly. It consists of multiple components that are detailed following. The accelerator pedal actuator system (**Image 4.8-63**) is a set of plastic injection molded components that are assembled together. The current OEM Chevrolet Silverado Brake Actuation Subsystem assembly has a mass of 10.80 kg.

#### 4.8.4.3 Mass Reduction Industry Trends

Brake-by-wire is a fairly new technology that has had some trouble getting traction in the auto industry. The idea of brake-by-wire is to replace the traditional hydraulic braking components such as the master cylinder, ABS module, steel brake lines, brake hoses, and brake fluid with electronic sensors and actuators/motors.

A hybrid brake-by-wire technology known as electro-hydraulic brake (EHB) system still utilizes a master cylinder that sends fluid pressure to the brake calipers based on an electric signal from the drivers brake pedal. With this technology, the mechanical connection between the brake pedal and master cylinder has been eliminated.

Although brake-by-wire is still being developed by some OEM's and automotive part suppliers, Mercedes has replaced all brake-by-wire applications with a conventional hydraulic system. Mercedes used an electro-hydraulic system developed by Daimler and Bosch called "Sensotronic Brake Control (SBC)" on the E-class models. Toyota launched their electro-hydraulic system called "Electronically Controlled Brake" system on the Estima and still uses it on several 2012 models such as the Lexus LFA.

##### 4.8.4.3.1 Master Cylinder and Reservoir

The baseline OEM Chevrolet Silverado master cylinder and reservoir sub-assembly (**Image 4.8-57**) is a multi-piece design of cast aluminum and machined fabrication assembled with various valving and sealing components. This overall sub-assembly has a mass of 1.04 kg. This system is already highly optimized for design and materials (aluminum and plastic) and therefore no further changes or solutions for mass reductions were identified for implementation.

**Image 4.8-57: Master Cylinder and Reservoir Current Sub-assembly**
*(Source: FEV, Inc.)*

#### 4.8.4.3.2 Brake Lines and Hoses

The baseline OEM Chevrolet Silverado brake lines and hoses (**Image 4.8-58**) are conventional tubing designs with steel walls and flared ends with threaded line fittings and appropriate brackets and fasteners added. This sub-subsystem has a mass of 1.93 kg. This system is very conventional, but no newer designs or systems were identified for replacement or improvement. The best solution choice for these components is to shorten the length of the brake lines required by optimizing the routing paths.

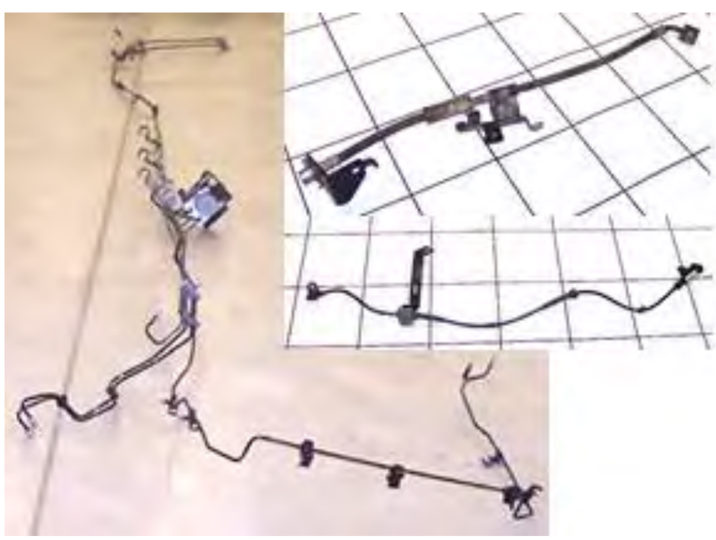


**Image 4.8-58: Brake Lines and Hoses Current Sub-assemblies**
*(Source: FEV, Inc.)*

### 4.8.4.3.3 Brake Pedal Actuator Sub-Assembly

The baseline OEM Chevrolet Silverado brake pedal actuator sub-assembly (**Image 4.8-59**) is a multi-piece design of stamped steel fabricated components welded together as an assembly along with springs, pins, levers, and fasteners. These components have a sub-assembly mass of 5.40 kg. This is a standard design configuration by nearly all OEMs allowing for adequate function while using a proven design and simple materials and processes. It is, however, not mass or cost efficient but instead is industry driven by allowing the continued utilization of existing capital equipment, tooling and reusing previous process/component designs.

**Image 4.8-59: Brake Pedal Actuator Current Sub-assembly**
*(Source: FEV, Inc.)*

#### *4.8.4.3.3.1 Brake Pedal Arm Frame Sub-Assembly*

While this steel brake pedal frame design is extremely common, there are some high-performance and luxury vehicle models that have begun utilizing alternate designs. These include new designs for the pedal frame and housing sub-assembly (**Image 4.8-60**). The new design utilizes a plastic framing and housing structure around the brake pedal arm sub-assembly. These injection molded frames simplify design by reducing components, ease assembly by eliminating welding and provide substantial weight savings. Other possible solutions use similar processing but different materials, including aluminum, high strength steel, magnesium, and titanium. This current welded sub-assembly has a 1.98 kg net mass.

**Image 4.8-60: Brake Pedal Arm Frame Current Sub-assembly**
*(Source: FEV, Inc.)*

#### *4.8.4.3.3.2 Brake Pedal Arm Side Plates*

While this steel brake pedal side plates (**Image 4.8-61**) design is common there are some high performance and luxury vehicle models that began to utilize alternate designs. These redesigns make use of lighter materials that allow a weight savings. Materials that are considered include: aluminum, titanium, magnesium, and high strength steel. These pieces are fabricated and machined to simplify design as provide substantial weight savings. This current sub-assembly has a net mass of 1.07 kg.

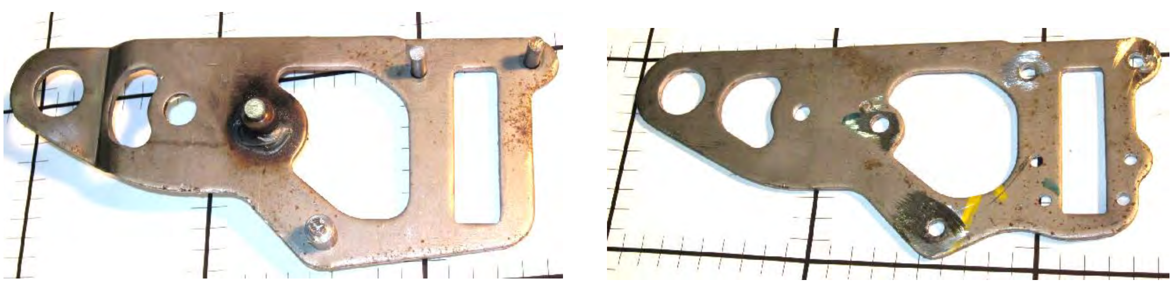


**Image 4.8-61: Brake Pedal Side Plate Current Sub-assembly**
*(Source: FEV, Inc.)*

#### *4.8.4.3.3.3 Brake Pedal Arm Assembly*

This steel brake pedal arm (**Image 4.8-62**) design is very common among OEMs. There are however, some high-performance and luxury vehicle models that have begun utilizing alternate designs. These include redesigns for material substitutions for the use of aluminum, titanium, magnesium, high-strength steel, and reinforced plastics. These new arms used simplified designs to reduce components and use light materials to provide substantial weight savings. This current welded sub-assembly has a net mass of 1.50 kg.

**Image 4.8-62: Brake Pedal Arm Current Sub-assembly**
*(Source: FEV, Inc.)*

4.8.4.3.4 Accelerator Pedal Actuator Sub-Assembly

The baseline OEM Chevrolet Silverado accelerator pedal actuator sub-assembly (**Image 4.8-63**) is a multi-piece design of injection molded components, springs, pins, levers and fasteners that are assembled together. This sub-assembly has a mass of 0.416 kg.

**Image 4.8-63: Accelerator Pedal Actuator Current Sub-assembly**
*(Source: FEV, Inc.)*

This configuration is very common in the automotive industry and used by nearly all OEMs. After researching for new designs, there were no significant mass reductions solutions that were found to be able to replace this unit and achieve any appreciable savings.

#### 4.8.4.4 Summary of Mass Reduction Concepts Considered

**Table 4.8-16** shows mass reduction ideas that were brainstormed and considered for the Brake Actuation Subsystem. These ideas include part modifications, material substitutions, and use of parts currently in production on other vehicles.

**Table 4.8-16: Summary of Mass Reduction Concepts Initially Considered for the Brake Actuation Subsystem**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Brake Actuation Subsystem** | | | |
| Accelerator Pedal | Mucell® lever, frame & pad (61) | ~10% wt save | Low risk - ~10% cost save |
| | | | |
| Brake Pedal Pad | Mucell® brake pedal pad (62) | ~10% wt save | Low risk - ~10% cost save |
| | | | |
| Brake Pedal Arm | Hollow plastic brake pedal and plastic arm (PA6-GF33) (63) | ~80% wt save | ~20% cost increase |
| | Brake pedal arm from hss (64) | ~10% wt save | ~3x cost increase |
| | Brake pedal arm from forged aluminum (65) | ~50% wt save | ~90% cost increase |
| | Brake pedal arm from magnesium (66) | ~60% wt save | ~100% cost increase |
| | Brake pedal arm from titanium (67) | ~30% wt save | ~7x cost increase |
| | | | |
| Brake Pedal Bracket | Aluminum support bracket (includes 2 sides, top, lower spacer & sensor brkt) (68) | ~50% wt save | ~80% cost increase |
| | Magnesium support bracket (includes 2 sides, top, lower spacer & sensor brkt) (69) | ~60% wt save | ~100% cost increase |
| | HSS support bracket (includes 2 sides, top, lower spacer & sensor brkt) (70) | ~10% wt save | ~3x cost increase |
| | Plastic (PA6 GF30) support bracket (includes 2 sides, top, lower spacer & sensor brkt) (71) | ~40% wt save | ~3x cost increase |
| | Replace from comparable A2MAC1 database (72) | 0 wt save | 0 cost change |

#### 4.8.4.5 Selection of Mass Reduction Ideas

**Table 4.8-17** shows the mass reduction ideas for the major components of the Brake Actuation Subsystem that were selected for detail evaluation. There are five components or sub-assemblies being redesigned and changed in order to achieve mass reductions.

**Table 4.8-17: Mass Reduction Ideas Selected for the Brake Actuation Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|---|---|---|
| 06 | 06 | 00 | Brake Actuation Subsystem | |
| 06 | 06 | 00 | Accelerator Pedal | Mold using Mucell® process |
| | | | | |
| 06 | 06 | 00 | Brake Pedal Arm | Make out of Plastic |
| | | | | |
| 06 | 06 | 00 | Brake Pedal Pad | Mold using Mucell® process |
| | | | | |
| 06 | 06 | 00 | Brake Pedal Brackets | Make out of cast Magnesium |
| | | | | |
| 06 | 06 | 00 | Brake Pedal Frame | Make out of cast Magnesium |

The mass saving solutions selected for the various components within the Brake Actuation Subsystem are summarized in greater detail in the following paragraphs.

#### 4.8.4.5.1 Master Cylinder and Reservoir

The baseline Chevrolet Silverado master cylinder and reservoir sub-assembly is already highly optimized for design and materials and therefore no further changes or solutions for mass reductions were identified.

#### 4.8.4.5.2 Brake Lines and Hoses

The baseline Chevrolet Silverado brake lines and hoses sub-assemblies are already highly optimized for design and materials and therefore no further changes or solutions for mass reductions were identified.

#### 4.8.4.5.3 Accelerator Pedal Assembly

The currently designed accelerator pedal assembly (**Image 4.8-64**) is already a good design regarding mass impact. This configuration is now very common in the automotive industry and used by nearly all OEMs. After researching for new designs, there are no significant mass reductions solutions found that could achieve any appreciable savings. However, the use of MuCell technology during the injection molding process of some of the larger plastic components does allow for a small weight savings of approximately

10% with almost no cost penalty. This newly processed sub-assembly results in a reduced net mass of 2.10 kg.

**Image 4.8-64: Accelerator Pedal Mass Reduced Assembly Example**
*(Source: FEV, Inc.)*

4.8.4.5.4 Brake Pedal Arm

The steel brake pedal arm (**Image 4.8-65**) design is now being changed to a redesign allowing the use PA6-GF. Due to the replacement of steel with an injection molded plastic, an additional material volume of 80-90% was made. This design configuration is becoming more common among OEMs and provides simple processing by injection molding and enabling a simplified design and substantial weight savings. This particular example shows a hollow insert being over-molded to further decrease weight and improve strength. This new mass reduced sub-assembly has a net mass of 0.749 kg.

**Image 4.8-65: Brake Pedal Arm Mass Reduced Sub-assembly Example**
*(Source: http://www.torquenews.com/auto-sector-stocks?page=27)*

### 4.8.4.5.5 Brake Pedal Pad

The currently designed brake pedal pad (**Image 4.8-66**) is typical for the automotive industry and used by nearly all OEMs. There are no significant mass reductions solutions found that could achieve any appreciable savings. However, the use of MuCell technology during the molding process does allow for a small weight savings of approximately 10% with almost no cost penalty. This newly processed part results in a reduced net mass of 0.092 kg.

**Image 4.8-66: Brake Pedal Pad Mass Reduced Component Example**
*(Source: FEV, Inc.)*

### 4.8.4.5.6 Brake Pedal Brackets

The currently designed flat and offset brake pedal brackets (**Image 4.8-67** and **Image 4.8-68**) are made from stamped steel. The selected redesign idea is to make the brackets out of cast magnesium. These newly processed parts result in a reduced net mass of 0.202 kg and 0.207 kg, respectively.

**Image 4.8-67 (Left): Flat Brake Pedal Pad Mass Reduced Component Example**

**Image 4.8-68 (Right): Offset Brake Pedal Pad Mass Reduced Component Example**
*(Sources: FEV, Inc.)*

#### 4.8.4.5.7 Brake Pedal Frame Assembly

The conventional steel brake pedal frame (**Image 4.8-69**) design has been replaced with a cast magnesium design. Due to the replacement of steel with magnesium, an additional material volume of 75-85% was made. This solution is being used in the 2013 Dodge RAM 1500 Laramie Crew Cab 4x4. These casted frames simplify design by reducing components and easing assembly while also providing substantial weight savings. This redesigned brake pedal frame has a reduced mass of 0.718 kg.

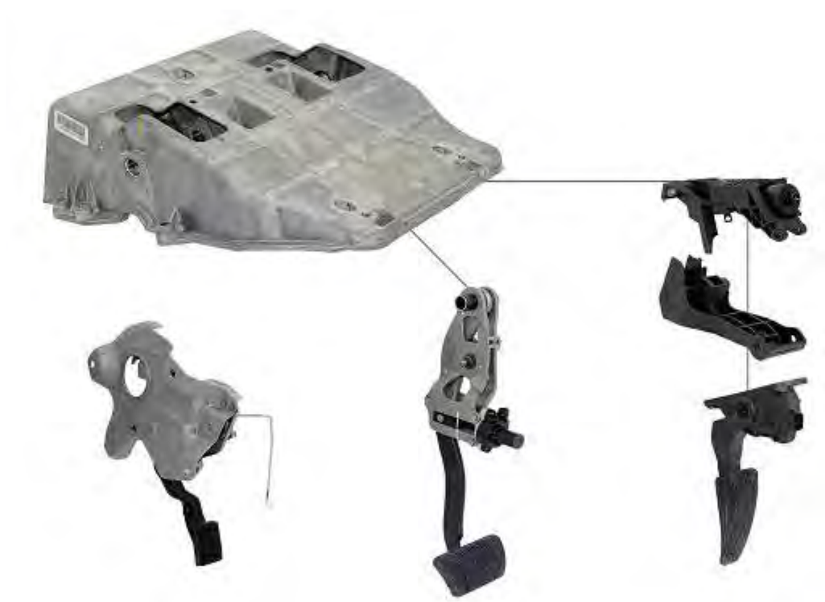


**Image 4.8-69: Brake Pedal Arm Frame Mass Reduced Assembly Example**
*(Source: https://a2mac1.com/AutoReverse/reversepart.)*

The net result of all of these changes within the Brake Actuation Sub-subsystem returns a new total mass of 8.14 kg.

Another brake actuator system design has also been developed by BMW (**Image 4.8-70**) for use in some of their high end luxury and performance vehicles. This unit utilizes plastic framing and pedal arms as well in order to reduce mass significantly.

**Image 4.8-70: Brake Pedal Actuator Mass Reduced Sub-assembly Example**
*(Source http://www.worldcarfans.com/111040531267/bmw-reveals-lightweight-component-innovations)*

### 4.8.4.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.8-18** shows the results of the mass reduction ideas that were evaluated for the Brake Actuation Subsystem. The implemented solutions resulted in a subsystem overall mass savings of 2.53 kg and a cost increase of $0.46.

**Table 4.8-18: Mass Reduction and Cost Impact for the Brake Actuation Subsystem**

| | | | | Net Value of Mass Reduction Ideas | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys/ Sub-Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 06 | 06 | 00 | Brake Actuation Subsystem | | | | | | |
| 06 | 06 | 02 | Actuator Assemblies | B | 2.53 | -$0.46 | -$0.18 | 23.7% | 0.10% |
| | | | | B | 2.53 (Decrease) | -$0.46 (Increase) | -$0.18 (Increase) | 23.7% | 0.10% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.8.5 Power Brake Subsystem (for Hydraulic)

#### 4.8.5.1 Subsystem Content Overview

As seen in **Table 4.8-19**, the Power Brake Subsystem consists of the vacuum booster system assembly.

**Table 4.8-19: Mass Breakdown by Sub-subsystem for the Power Brake (for Hydraulic) Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 06 | 07 | 00 | Power Brake Subsystem (for Hydraulic) | |
| 06 | 07 | 01 | Vacuum Booster System Asm | 4.24 |
| | | | Total Subsystem Mass = | 4.24 |
| | | | Total System Mass = | 101.0 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 4.20% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.17% |

#### 4.8.5.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado Power Brake Subsystem (**Image 4.8-71**) follows typical industry standards in using a vacuum-actuated booster. The booster is a metal canister that contains a valve and diaphragm and uses vacuum from the engine to multiply the force a driver's foot applies to the master cylinder. A rod going through the center of the canister connects to the master cylinder's piston on one side and to the pedal linkage on the other. The booster also includes a check valve that maintains vacuum in the booster when the engine is turned off, or if a leak forms in a vacuum hose. The vacuum booster has to be able to provide enough volume and pressure within the brake line system for a driver to make several stops in the event that the engine stops running.

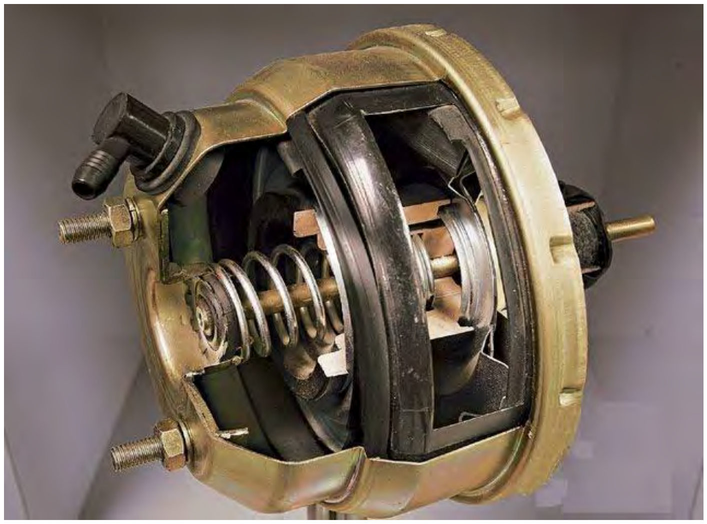


**Image 4.8-71: Brake Power Brake Subsystem Major Sub-assembly Example**
*(Source:http://www.superChevrolet.com/technical/chassis/brakes/sucp_0901_power_brake_boosters)*

#### 4.8.5.3 Mass Reduction Industry Trends

Some manufacturers have begun to implement a new system design that utilizes solenoids and valves in order to maintain system pressure during various driving conditions. This allows for removal of the typical conventional vacuum booster system configuration. This smaller, but much more expensive system usually requires the addition of wiring harnesses and control modules to process I/Os and regulate the system operation. But this small addition of materials is minor when compared to the overall mass saved by removing the booster unit. The result of this system exchange results in a significant weight savings. This electro-mechanical system (**Image 4.8-72**) configuration is utilized in the 2008 Toyota Prius. Another example of this technology is the Hyperbrake™ system (**Image 4.8-73**) by Janel Hydro. It claims to completely eliminate the vacuum booster by use of pistons and cylinders to amplify the hydraulic pressure of the brake fluid.

**Image 4.8-72: Toyota Prius Hydraulic Pressure Booster**
*(Source: Lotus – 2010 March EPA Report)*


**Image 4.8-73: Janel Hyperbrake Hydraulic Pressure Booster**
*(Source: http://www.janelhydro.com/)*

Staying within the traditional brake booster design, Continental recently announced the development of an all aluminum brake booster called the Booster Gen. III (**Image 4.8-74**). This third generation design, has a reduced weight of nearly 50% and is 15 mm shorter.

**Image 4.8-74: Continental's All Aluminum Brake Booster**
*(Source: http://www.automotiveworld.com/news-releases/continental-develops-a-new-generation-of-lightweight-brake-boosters/)*

#### 4.8.5.3.1 Vacuum Booster Sub-Assembly

The baseline Chevrolet Silverado Vacuum booster assembly (**Image 4.8-75**) is a multi-piece steel design. The major components within this assembly are made from stamped steel (front shell – **Image 4.8-76**; rear shell – **Image 4.8-77**; front backing plate, diaphragm – **Image 4.8-82**; rear backing plate, diaphragm – **Image 4.8-83**; spacer plate, diaphragm – **Image 4.8-84**), small fabricated steel parts (piston, actuator – **Image 4.8-78**; stud (MC to booster) – **Image 4.8-79**; stud (booster to firewall) – **Image 4.8-80**; pivot shaft, actuator – **Image 4.8-81**) and a few plastic and rubber molded pieces (plunger Boot, diaphragm, piston housing). These components are then assembled with various processing methods and fasteners into the vacuum booster system. Together these components have a net sub-assembly mass of 5.50 kg.

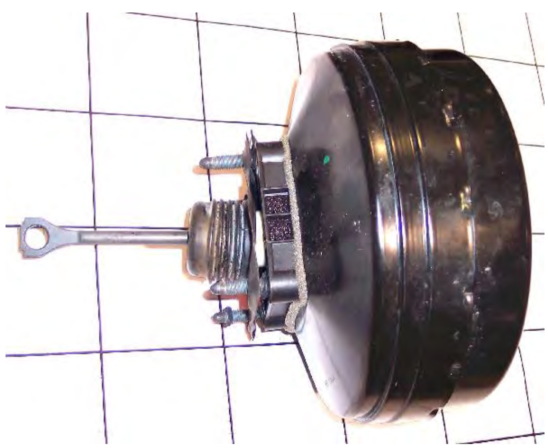


**Image 4.8-75: Brake Pedal Actuator Mass Current Sub-assembly**
*(Source: FEV, Inc.)*

#### *4.8.5.3.1.1 Front Shell*

This booster front shell (**Image 4.8-76**) is of a standard design configuration. It is fabricated from a one-piece sheet metal stamping and painted for corrosion resistance. There are a few alternate designs that have been tried in other vehicles. These new designs utilize different materials including molded reinforced plastics, spun aluminum, and HSS stampings. These alternative materials allow for simple manufacturing while still providing substantial weight savings. The current steel front shell has a mass of 1.01 kg.


**Image 4.8-76: Vacuum Booster Front Shell Current Component**
*(Source: FEV, Inc.)*

#### *4.8.5.3.1.2 Rear Shell*

The current booster rear shell (**Image 4.8-77**) is a typical design used by many OEM manufacturers. It is a fabricated one piece sheet metal stamping, painted for corrosion resistance. There are some alternate designs that have been tried in other applications. These other configurations utilize different materials including molded reinforced plastics, spun aluminum and HSS stampings. These materials provide weight savings while still allowing for simple manufacturing processes. The Silverado rear shell has a mass of 0.782 kg.

**Image 4.8-77: Vacuum Booster Rear Shell Current Component**
*(Source: FEV, Inc.)*

#### *4.8.5.3.1.3 Piston, Actuator*

The machined steel piston, actuator (**Image 4.8-78**) design is very common among OEMs. There are other material alternatives that allow for mass savings. These include redesigns for material substitutions for the use of aluminum, titanium, magnesium, and HSS. The Silverado piston actuator component has a mass of 0.065 kg.

**Image 4.8-78: Piston, Actuator Current Component**
*(Source: FEV, Inc.)*

#### *4.8.5.3.1.4 Stud (MC to Booster)*

The machined Stud (MC to booster) (**Image 4.8-79**) design is very common among OEMs. There are other material alternatives that allow for mass savings. These include redesigns for material substitutions for the use of aluminum, titanium, and HSS. The Silverado stud (MC to booster) component has a mass of 0.043 kg.

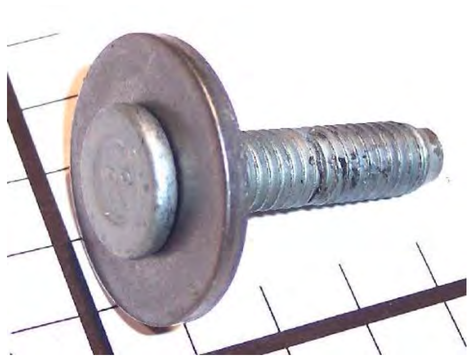


**Image 4.8-79: Stud (MC to Booster) Current Component**
*(Source: FEV, Inc.)*

#### *4.8.5.3.1.5 Stud (Booster to Firewall)*

The machined stud (booster to firewall) (**Image 4.8-80**) design is very common among OEMs. There are other material alternatives that allow for mass savings. These include redesigns for material substitutions for the use of aluminum, titanium, magnesium, HSS, and reinforced plastics. The Silverado stud (booster to firewall) component has a mass of 0.038 kg.

**Image 4.8-80: Stud (Booster to Firewall) Current Component**
*(Source: FEV, Inc.)*

#### *4.8.5.3.1.6 Pivot Shaft, Actuator*

The machined pivot shaft, actuator (**Image 4.8-81**) design is very common among OEMs. There are other material alternatives that allow for mass savings. These include redesigns for material substitutions for the use of aluminum, titanium, and HSS. The Silverado pivot shaft, actuator component has a mass of 0.095 kg.

**Image 4.8-81: Pivot Shaft, Actuator Current Component**
*(Source: FEV, Inc.)*

### *4.8.5.3.1.7 Front Backing Plate, Diaphragm*

The stamped steel Front Backing Plate, Diaphragm (**Image 4.8-82**) design is very common among OEMs. There are other material alternatives that allow for mass savings. These include redesigns for material substitutions for the use of aluminum, titanium, magnesium, HSS, and reinforced plastics. The Silverado front backing plate, diaphragm component has a mass of 0.385 kg.

**Image 4.8-82: Vacuum Booster Front Backing Plate, Diaphragm Current Component**
*(Source: FEV, Inc.)*

### *4.8.5.3.1.8 Rear Backing Plate, Diaphragm*

The baseline OEM Chevrolet Silverado rear backing plate, diaphragm (**Image 4.8-83**) is a single-piece, stamped steel design. This Silverado rear backing plate, diaphragm component has a mass of 0.385 kg.

**Image 4.8-83: Vacuum Booster Rear Backing Plate, Diaphragm Current Component**
*(Source: FEV, Inc.)*

#### *4.8.5.3.1.9 Spacer Plate, Diaphragm*

The baseline OEM Chevrolet Silverado spacer plate, diaphragm (**Image 4.8-84**) is a single-piece, stamped steel design. This Silverado rear backing plate, diaphragm component has a mass of 0.376 kg.

**Image 4.8-84: Vacuum Booster Spacer Plate, Diaphragm Current Component**
*(Source: FEV, Inc.)*

### 4.8.5.4 Summary of Mass Reduction Concepts Considered

**Table 4.8-20** shows mass reduction ideas that were brainstormed and considered for the Power Brake Subsystem. Ideas include part modifications and material substitutions for nine different components.

**Table 4.8-20: Summary of Mass Reduction Concepts Initially Considered for the Power Brake Subsystem (for Hydraulic)**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Power Brake Subsystem (for Hydraulic)** | | | |
| Front Shell | Make vacuum brake booster shell (front) out of spun aluminum (73) | ~50% wt save | ~100% cost increase |
| | Make vacuum brake booster shell (front) out of HSS (74) | ~10% wt save | ~3x cost increase |
| | Make vacuum brake booster shell (front) out of die cast Magnesium (75) | ~60% wt save | ~80% cost increase |
| | Make vacuum brake booster shell (front) out of Titanium (76) | ~30% wt save | ~7x cost increase |
| | Make vacuum brake booster shell (front) out of molded & ribbed PA6 GF30 (77) | ~40% wt save | ~3x cost increase |
| | | | |
| Rear Shell | Make vacuum brake booster shell (rear) out of spun aluminum (78) | ~50% wt save | ~100% cost increase |
| | Make vacuum brake booster shell (rear) out of HSS (79) | ~10% wt save | ~3x cost increase |
| | Make vacuum brake booster shell (rear) out of die cast Magnesium (80) | ~60% wt save | ~80% cost increase |
| | Make vacuum brake booster shell (rear) out of Titanium (81) | ~30% wt save | ~7x cost increase |
| | Make vacuum brake booster shell (rear) out of molded & ribbed PA6 GF30 (82) | ~40% wt save | ~3x cost increase |
| | | | |
| Piston, Actuator | Make booster piston, actuator out of forged aluminum (83) | ~50% wt save | ~90% cost increase |
| | Make booster piston, actuator out of HSS (84) | ~10% wt save | ~3x cost increase |
| | Make booster piston, actuator out of Magnesium (85) | ~60% wt save | ~75% cost increase |
| | Make booster piston, actuator out of Titanium (86) | ~30% wt save | ~7x cost increase |
| | | | |
| Studs - MC to Booster | Make studs - long out of forged aluminum (87) | ~50% wt save | ~100% cost increase |
| | Make studs - long out of HSS (88) | ~10% wt save | ~3x cost increase |
| | Make studs - long out of Titanium (89) | ~30% wt save | ~8x cost increase |
| | | | |
| Studs - Booster to Firewall | Make studs - long out of forged aluminum (91) | ~50% wt save | ~95% cost increase |
| | Make studs - long out of HSS (92) | ~10% wt save | ~3x cost increase |
| | Make studs - long out of Titanium (93) | ~30% wt save | ~8x cost increase |
| | | | |
| Pivot Shaft, Actuator | Make shaft, center plunger out of forged aluminum (94) | ~55% wt save | ~70% cost increase |
| | Make shaft, center plunger out of HSS (95) | ~10% wt save | ~3x cost increase |
| | Make shaft, center plunger out of Titanium (96) | ~60% wt save | ~4x cost increase |

**Table 4.8-20 continued next page**

**Table 4.8-20 (Cont'd)**

| Component/ Assembly | Mass Reduction Idea | Estimated Impact | Risk & Trade-offs and/or Benefits |
|---|---|---|---|
| **Power Brake Subsystem (for Hydraulic)** | | | |
| Front Backing Plate | Make backing plate out of stamped aluminum (97) | ~60% wt save | ~50% cost increase |
| | Make backing plate out of HSS (98) | ~10% wt save | ~3x cost increase |
| | Make backing plate out of ABS plastic (99) | ~30% wt save | ~70% cost increase |
| | Make backing plate out of magnesium (100) | ~60% wt save | ~70% cost increase |
| | | | |
| Rear Backing Plate | Make backing plate out of stamped aluminum (101) | ~60% wt save | ~40% cost increase |
| | Make backing plate out of HSS (102) | ~10% wt save | ~3x cost increase |
| | Make backing plate out of ABS plastic (103) | ~30% wt save | ~70% cost increase |
| | Make backing plate out of magnesium (104) | ~60% wt save | ~70% cost increase |
| | | | |
| Backing Plate Spacer | Make backing plate out of stamped aluminum (105) | ~50% wt save | ~80% cost increase |
| | Make backing plate out of HSS (106) | ~10% wt save | ~3x cost increase |
| | Make backing plate out of ABS plastic (107) | ~30% wt save | ~70% cost increase |
| | Make backing plate out of magnesium (108) | ~60% wt save | ~70% cost increase |
| | | | |

### 4.8.5.5 Selection of Mass Reduction Ideas

**Table 4.8-21** shows mass reduction ideas for the Power Brake Subsystem that were selected as final solutions for detailed evaluation for both mass and cost.

**Table 4.8-21: Mass Reduction Ideas Selected for Detailed Power Brake (for Hydraulic) Subsystem Analysis**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas selected for Detail Evaluation |
|---|---|---|---|---|
| **06** | **07** | **00** | **Power Brake Subsystem (for Hydraulic)** | |
| 06 | 07 | 00 | Vacuum Brake Booster Shell - Front | Make out of die cast Magnesium |
| | | | | |
| 06 | 07 | 00 | Vacuum Brake Booster Shell - Rear | Make out of die cast Magnesium |
| | | | | |
| 06 | 07 | 00 | Piston, Actuator | Make out of die cast Magnesium |
| | | | | |
| 06 | 07 | 00 | Studs - MC to BM | Make out of Forged Aluminum |
| | | | | |
| 06 | 07 | 00 | Studs - Booster to Firewall | Make out of Forged Aluminum |
| | | | | |
| 06 | 07 | 00 | Pivot Shaft, Actuator | Make out of Titanium |
| | | | | |
| 06 | 07 | 00 | Backing Plate, Front | Make out of die cast Magnesium |
| | | | | |
| 06 | 07 | 00 | Backing Plate, Rear | Make out of stamped Aluminum |
| | | | | |
| 06 | 07 | 00 | Backing Plate, Spacer | Make out of die cast Magnesium |

#### 4.8.5.5.1 Vacuum Booster Sub-Assembly

The new brake vacuum booster sub-assembly (**Image 4.8-85**) is still a multi-piece design as the original was but now using optimized, mass reduced components where applicable. With these nine new component designs assembled together, this new booster sub-assembly now has a reduced mass of 2.71 kg.

**Image 4.8-85: Vacuum Booster Mass Reduced Sub-assembly Example**
*(Source: http://brakematerialsandparts.webs.com/boosterrebuilding.htm)*

##### *4.8.5.5.1.1 Front Shell*

The conventional steel vacuum booster front shell (**Image 4.8-86**) design has been replaced with a cast magnesium design. Due to the replacement of steel with magnesium, an additional material volume of 75-85% was made. This design is not currently in any high-production applications, but should become more accepted in lighter applications in future model releases. This cast magnesium shell provides substantial weight savings and has a reduced mass of 0.427 kg.

**Image 4.8-86: Vacuum Booster Front Shell Mass Reduced Component Example**
*(Source: http://images.wrenchead.com/smartpages/partinfo_resize/A1C/532282-01.jpg)*

#### *4.8.5.5.1.2 Rear Shell*

The steel vacuum booster rear shell (**Image 4.8-87**) design has been replaced with a single-piece cast magnesium component. Due to the replacement of steel with magnesium, an additional material volume of 75-85% was made. This design is not commonly used by OEMs but can easily be utilized in many current applications. This casted shell retains a simplified design and uses a common manufacturing process while still allowing for reasonable weight savings. This redesigned component has a reduced mass of 0.330 kg.

**Image 4.8-87: Vacuum Booster Rear Shell Reduced Mass Component Example**
*(Source: http://images.wrenchead.com/smartpages/partinfo_resize/A1C/532282-01.jpg)*

#### *4.8.5.5.1.3 Piston Actuator*

The steel Piston Actuator (**Image 4.8-88**) design is now being replaced with a cast magnesium design. Due to the replacement of steel with cast magnesium, an additional material volume of 60-70% was made. This new mass reduced part has weight of 0.037 kg.

**Image 4.8-88: Piston Actuator**
*(Source : FEV, Inc.)*

#### *4.8.5.5.1.4 Stud, Booster to Firewall*

The machined steel stud (booster to firewall) (**Image 4.8-89**) design is being replaced with a forged aluminum design. Due to the replacement of steel with aluminum, an additional material volume of 50-55% was made. This new mass reduced part has weight of 0.021 kg.

**Image 4.8-89: Stud (Booster to Firewall) Current Component**
*(Source: FEV, Inc.)*

#### *4.8.5.5.1.5 Stud, Master Cylinder to Booster*

The machined steel stud (MC to booster) (**Image 4.8-90**) design is being replaced with a forged aluminum design. Due to the replacement of steel with aluminum, an additional material volume of 50-55% was made. This new mass reduced part has weight of 0.023 kg.

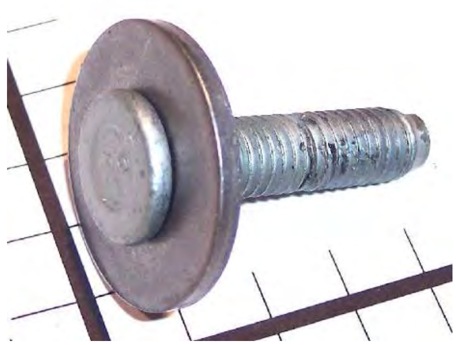


**Image 4.8-90: Stud (MC to Booster) Current Component**
*(Source: FEV, Inc.)*

#### *4.8.5.5.1.6 Pivot Shaft, Actuator*

The steel machined pivot shaft, actuator (**Image 4.8-91**) design is now being replaced with a titanium design. Due to the replacement of steel with titanium, an additional material volume of 20-30% was made. This new mass reduced part has weight of 0.068 kg.

**Image 4.8-91: Pivot Shaft, Actuator Current Component**
*(Source: FEV, Inc.)*

#### *4.8.5.5.1.7 Front Backing Plate*

The steel front backing plate (**Image 4.8-92**) design has been replaced with a single-piece cast magnesium component. Due to the replacement of steel with magnesium, an additional material volume of 75-85% was made. This design is not commonly used by OEMs but can easily be utilized in many current applications. This casted plate retains a simplified design and uses a common manufacturing process while still allowing for reasonable weight savings. This redesigned component has a reduced mass of 0.162 kg.

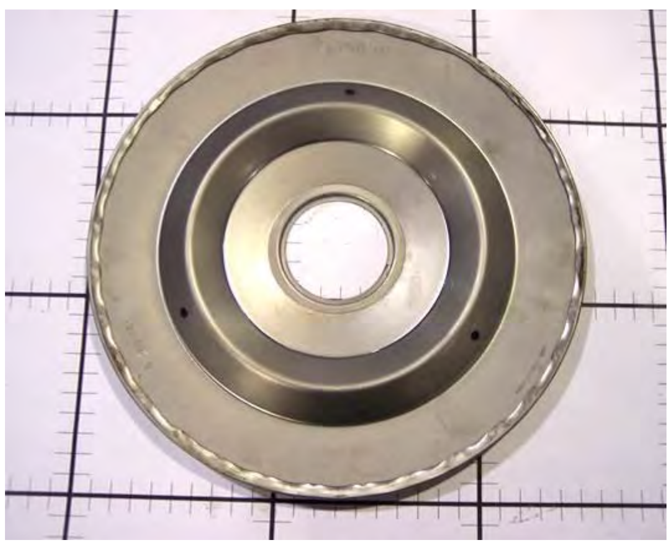


**Image 4.8-92: Vacuum Booster Front Backing Plate Reduced Mass Component Example**
*(Source: FEV, Inc.)*

#### *4.8.5.5.1.8 Rear Backing Plate*

The steel rear backing plate (**Image 4.8-93**) design has been replaced with a single-piece cast aluminum component. Due to the replacement of steel with aluminum, an additional material volume of 50-55% was made. This design is not commonly used by OEMs but can easily be utilized in many current applications. This casted plate retains a simplified design and uses a common manufacturing process while still allowing for reasonable weight savings. This redesigned component has a reduced mass of 0.208 kg.

**Image 4.8-93: Vacuum Booster Rear Backing Plate Reduced Mass Component Example**
*(Source: FEV, Inc.)*

#### *4.8.5.5.1.9 Spacer Plate*

The steel spacer plate (**Image 4.8-94**) design has been replaced with a single-piece cast magnesium component. Due to the replacement of steel with magnesium, an additional material volume of 75-85% was made. This design is not commonly used by OEMs but can easily be utilized in many current applications. This casted plate retains a simplified design and uses a common manufacturing process while still allowing for reasonable weight savings. This redesigned component has a reduced mass of 0.231 kg.

**Image 4.8-94: Vacuum Booster Spacer Plate Reduced Mass Component Example**
*(Source: FEV, Inc.)*

#### 4.8.5.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.8-22** shows the results of the mass reduction ideas that were evaluated and implemented for the Power Brake Subsystem. This included redesigns and modifications being made to nine different components. The implemented solutions resulted in a subsystem overall mass savings of 1.58kg and a cost increase of $24.64.

**Table 4.8-22: Mass Reduction and Cost Impact for the Power Brake (Hydraulic) Subsystem**

| | | | | Net Value of Mass Reduction Ideas | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys/ Sub-Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 06 | 07 | 00 | Power Brake (for Hydraulic) Subsystem | | | | | | |
| 06 | 07 | 01 | Vacuum Booster System Asm | X | 1.58 | -$24.64 | -$15.57 | 37.3% | 0.06% |
| | | | | X | 1.58 (Decrease) | -$24.64 (Increase) | -$15.57 (Increase) | 37.3% | 0.06% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.8.6 Secondary Mass Reduction / Compounding

#### 4.8.6.1 Subsystem Content Overview

The intent of investigating secondary mass savings is to quantify how much brake system mass could be further reduced by reducing the vehicle mass.

To calculate the allowable secondary mass reduction (**Table 4.8-23**), the Chevrolet Silverado baseline curb weight was reduced by 20%. Next, the Gross Combination Weight Rating (GCWR) was lightened by adding the lightened curb weight to the difference between the baseline GCWR and baseline curb weight (1963+(6804-2454)). The lightened GCWR and baseline GCWR were ratioed to obtain the allowable mass reduction factor of 7.2%.

**Table 4.8-23: Allowable Secondary Mass Reduction Calculation**

| Chevrolet Silverado Brake System<br>Secondary Mass Reduction/Compounding Calculation | |
|---|---|
| Baseline Gross Combination Weight Rating (GCWR) | 6804 |
| Baseline Curb Weight (kgs) | 2454 |
| | |
| Lightened (GCWR) | 6313 |
| Lightened (20%) Curb Weight (kgs) | 1963 |
| | |
| Allowable Mass Reduction<br>(Lightened (GCWR)/Baseline (GCWR) | **7.2%** |

Brake system components such as Rotors, Calipers, Caliper Mounting Brackets, and Drums are sized based on the gross combination weight rating. Secondary mass savings (**Table 4.8-24**) were derived from reduced component masses previously calculated for lightweighting technologies. All other components like those associated with the accessories and fasteners were not affected and masses were unchanged. The result is 2.01 kg of additional mass savings based on downsizing.

**Table 4.8-24: Chevrolet Silverado Brake System Compounded Mass Savings by Component**

| | Component | New Mass (kg) | Downsizing Approach | % Reduction | Compounded Mass Savings (kg) |
|---|---|---|---|---|---|
| 1 | Front Brake Rotor Asm (2) | 11 | Area Reduction | 7.2 | 0.764 |
| 2 | Caliper Housing (2) | 3.19 | Area Reduction | 7.2 | 0.230 |
| 3 | Caliper Mounting Bracket (2) | 1.38 | Area Reduction | 7.2 | 0.100 |
| 4 | Rear Brake Drum (2) | 8.40 | Area Reduction | 7.2 | 0.605 |
| 5 | Backing Plate, Rear Brake Drum (2) | 4.38 | Area Reduction | 7.2 | 0.315 |
| | **Total (kg)** | **29** | | | **2.01** |

Material savings for compounded components was totaled to estimate the cost impact of downsizing. Labor and burden costs were considered unchanged.

**Table 4.8-25** details the mass and cost impact of all lightweighting activities and compounding. These figures are based on downsizing the already lightweighted concept as outlined in previous sections. The total mass reduction achieved for the Brake System is 45.8 kg at a total cost impact of $148.92.

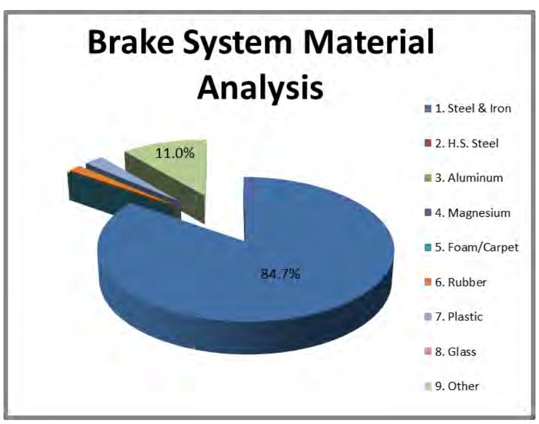
**Table 4.8-25: Mass Reduction and Cost Impact for Brake System Secondary Mass Savings**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 06 | 00 | 00 | Brake System | | | | | | | | |
| 06 | 03 | 00 | Front Rotor/Drum and Shield Subsystem | 22.0 | 1.06 | 23.1 | -$56.20 | $10.84 | -$45.35 | -$1.97 | 0.94% |
| 06 | 04 | 00 | Rear Rotor/Drum and Shield Subsystem | 16.3 | 0.89 | 17.2 | -$71.02 | $8.11 | -$62.91 | -$3.66 | 0.70% |
| 06 | 05 | 00 | Parking Brake and Actuation Subsystem | 1.45 | 0.00 | 1.45 | -$15.56 | $0.00 | -$15.56 | -$10.72 | 0.06% |
| 06 | 06 | 00 | Brake Actuation Subsystem | 2.53 | 0.00 | 2.53 | -$0.46 | $0.00 | -$0.46 | -$0.18 | 0.10% |
| 06 | 07 | 00 | Power Brake Subsystem (for Hydraulic) | 1.58 | 0.00 | 1.58 | -$24.64 | $0.00 | -$24.64 | -$15.57 | 0.06% |
| | | | | 43.9 (Decrease) | 1.96 (Decrease) | 45.8 (Decrease) | -$167.87 (Increase) | $18.95 (Decrease) | -$148.92 (Increase) | -$3.25 (Increase) | 1.87% |

## 4.8.7 Brake System Material Analysis

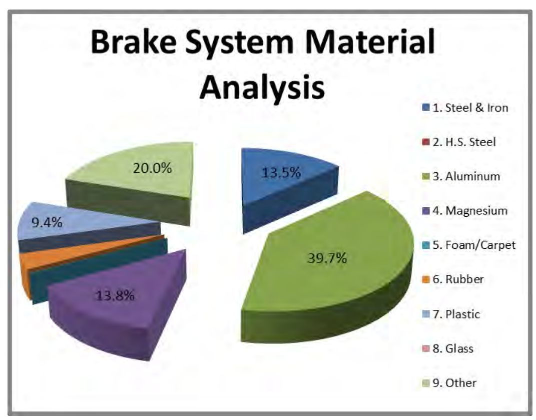
The Material Categories for the Baseline Brake System and for the Total Mass Reduced Brake System are shown in **Figure 4.8-4**. "High Strength Steel decreased from 85.6 kg to 7.09 kg. As can be seen, "Aluminum" increased significantly from 0.0 kg (baseline mass) to 22.9 kg (total mass reduction) and "Magnesium" also increased from 0.0 kg (baseline mass) to 7.23 kg (total mass reduction).

**Baseline Brake System**




| | | Material Categories: |
|---|---|---|
| 84.7% | 85.6 | 1. Steel & Iron |
| 0.0% | 0.0 | 2. H.S. Steel |
| 0.0% | 0.0 | 3. Aluminum |
| 0.0% | 0.0 | 4. Magnesium |
| 0.038% | 0.0 | 5. Foam/Carpet |
| 1.71% | 1.72 | 6. Rubber |
| 2.51% | 2.53 | 7. Plastic |
| 0.0% | 0.0 | 8. Glass |
| 11.0% | 11.2 | 9. Other |
| 100% | 101.0 | TOTAL |

**Total Mass Reduced Brake System**




| | | Material Categories: |
|---|---|---|
| 13.0% | 7.09 | 1. Steel & Iron |
| 0.0% | 0.0 | 2. H.S. Steel |
| 41.9% | 22.9 | 3. Aluminum |
| 13.3% | 7.23 | 4. Magnesium |
| 0.1% | 0.0 | 5. Foam/Carpet |
| 3.5% | 1.89 | 6. Rubber |
| 9.0% | 4.92 | 7. Plastic |
| 0.0% | 0.0 | 8. Glass |
| 19.3% | 10.5 | 9. Other |
| 100% | 54.6 | TOTAL |

**Figure 4.8-4: Baseline and Total Mass Reduced Brake System Material Distribution**

## 4.9 Exhaust System

An exhaust system is tubing used to guide reaction exhaust gases away from a controlled combustion inside an engine. The entire system conveys burnt gases from the engine, expelling these toxic and/or noxious gases through one or more exhaust pipes. Depending on the overall system design, the exhaust gas may flow through one or more of the following: cylinder head and exhaust manifold; a turbocharger (to increase engine power); a catalytic converter (to reduce air pollution); a muffler (to lessen noise). **Image 4.9-1** shows the Chevrolet Silverado exhaust system.

The Exhaust System is comprised of the Acoustical Control Components Subsystem (**Table 4.9-1**).

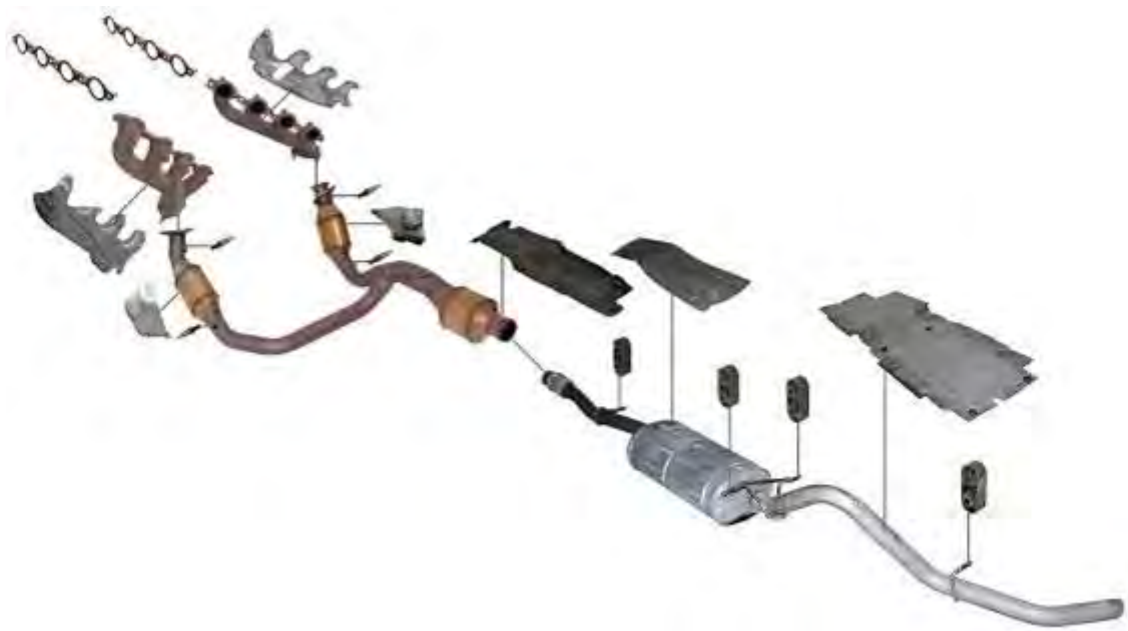
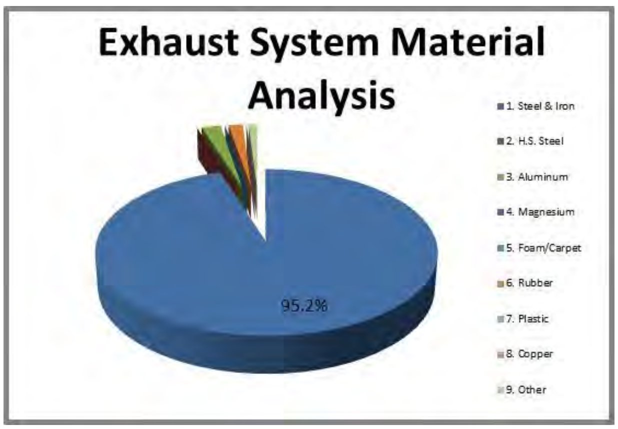


**Image 4.9-1: Chevrolet Silverado Exhaust System**
*(Source: A2mac1 data base)*

**Table 4.9-1: Mass Breakdown by Subsystem for Exhaust System.**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 09 | 00 | 00 | Exhaust System | |
| 09 | 01 | 00 | Acoustical Control Components | 38.370 |
| | | | Total System Mass = | 38.370 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 1.56% |




| | | Material Categories: |
|---|---|---|
| 95.2% | 36.514 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 2.2% | 0.841 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 1.7% | 0.636 | 6. Rubber |
| 0.0% | 0.000 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 1.0% | 0.379 | 9. Other |
| 100% | 38.370 | TOTAL |

**Figure 4.9-1: Calculated material content for the Exhaust System base BOM**

**Table 4.9-2** provides the mass and cost impact for the exhaust subsystems.

**Table 4.9-2: Mass Reduction and Cost Impact for Exhaust Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys./ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 09 | 00 | 00 | Exhaust System | | | | | | |
| 09 | 01 | 00 | Acoustical Control Components | D | 6.340 | -$19.54 | -$3.08 | 16.52% | 0.26% |
| | | | | D | 6.340 (Decrease) | -$19.54 (Increase) | -$3.08 (Increase) | 16.52% | 0.26% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.9.1 Acoustical Control Components Subsystem

### 4.9.1.1 Subsystem Content Overview

As seen in **Table 4.9-3**, the Crossover Pipe Assembly, Expansion Clamp Assembly and Muffler Sub-subsystems are included in the Acoustical Control Components Subsystem.

**Table 4.9-3: Mass Breakdown by Sub-subsystem for Acoustical Control Components Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 09 | 00 | 00 | Exhaust System | |
| 09 | 01 | 01 | Cross Over Pipe Assembly | 15.532 |
| 09 | 01 | 02 | Expansion clamp assy | 3.806 |
| 09 | 01 | 03 | Muffler | 19.032 |
| | | | Total Subsystem Mass = | 38.370 |
| | | | Total System Mass = | 38.370 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 100.00% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.56% |

#### 4.9.1.2 Chevrolet Silverado Baseline Subsystem Technology

For the Acoustic Control Components Subsystem, the total 38.4 kg weight does include the muffler. It also includes the front crossover pipe assembly section, which includes three catalytic converters. The crossover pipe and the down pipe are made of 409 grade stainless steel (**Image 4.9-2**).

**Image 4.9-2: Crossover Pipe Assembly**
*(Source: A2mac1 data base)*

The job of the catalytic converter is to convert harmful pollutants into less harmful emissions before expulsion from the car's exhaust system. The converters consist of a cordierite structure coated with a metal catalyst, usually platinum, rhodium, and/or palladium. The idea is to create a structure that exposes the maximum surface area of catalyst to the exhaust stream while also minimizing the amount of catalyst required, as the materials are extremely expensive. Some of the newest converters even use gold mixed with the more traditional catalysts. Gold is cheaper than the other materials and could increase oxidation, the chemical reaction that reduces pollutants, by up to 40%.

The main emissions from a car engine are:

- **Nitrogen gas** ($N_2$) - Air is 78% nitrogen gas, and most of this passes right through the car engine.
- **Carbon dioxide** ($CO_2$) - This is one product of combustion. The carbon in the fuel bonds with the oxygen in the air.
- **Water vapor** ($H_2O$) - This is another product of combustion. The hydrogen in the fuel bonds with the oxygen in the air.

These emissions are mostly benign, although carbon dioxide emissions are believed to contribute to global warming. Because the combustion process is never perfect, some smaller amounts of more harmful emissions are also produced in car engines. Catalytic converters are designed to reduce all three:

- **Carbon monoxide** (CO) is a poisonous gas that is colorless and odorless.
- **Hydrocarbons or volatile organic compounds** (VOCs) are a major component of smog produced mostly from evaporated, unburned fuel.
- **Nitrogen oxides** (NO and $NO_2$, together called $NO_x$) are a contributor to smog and acid rain, which also causes irritation to human mucus membranes.

**Image 4.9-10** shows how the catalytic converter works.


**Image 4.9-3: Catalytic Converter**
*(Source: Google Images)*

In **Image 4.9-10** is a large pile of platinum lined catalytic converter cores and the basic ceramic core.

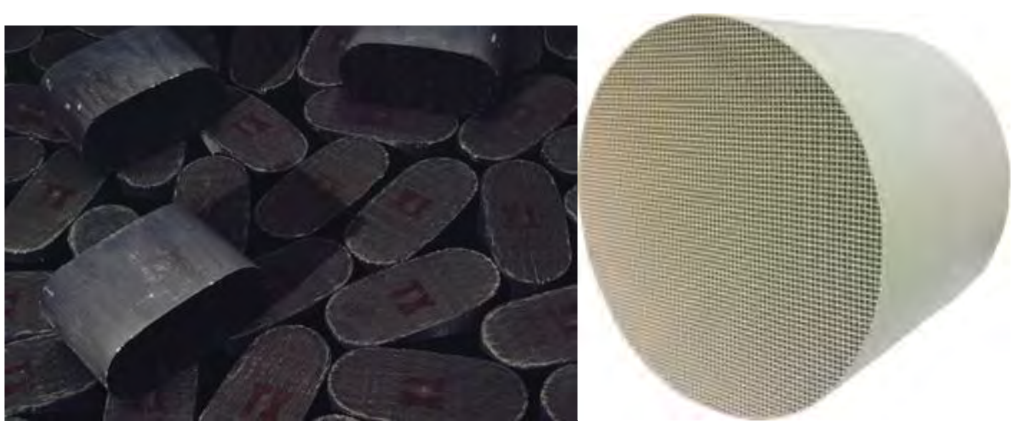


**Image 4.9-4: Catalytic Converter Cores**
*(Source: howstuffworks.com/Getty images/Google Images)*

Touchstone Research Laboratory® in West Virginia created a potential new structure to replace the cordierite used in today's catalytic converter. The product, under the company name CFOAM®, has the potential to reduce the mass by up to 31% and at a cost savings of up to 94% using coal in place of cordierite. The actual cost savings will vary depending on several factors, including the market price of coal, the specific coal needed for producing the best converter, and any additional steps that may be needed for oxidation protection.


**Image 4.9-5: CFOAM® Carbon Foam**
*(Source: Touchstone Research Laboratory)*

Advances in catalytic converters and emission systems have reduced emissions by more than 95% from the uncontrolled period of the 1960s. In order for a catalytic converter to perform efficiently, it must allow for the exhaust gases to pass in close proximity to the catalytic materials on the substrate's surface. Also, the element must at the same time create a low restriction in the flow of exhaust gases. Furthermore, as emission restrictions tighten even more, increasing emphasis is being placed on the time it takes to bring a catalytic converter to operating temperature, during which time 60%-80% of all non-methane hydrocarbons (NMHC) and carbon monoxide (CO) emissions occur. CFOAM Carbon Foam's open cell structure presents an ideal high surface area catalyst substrate in which the flow path through the foam creates a mixing effect to the exhaust stream. This mixing effect increases exposure of the exhaust gases to the catalysts and can increase the efficiency of the converter. By controlling the electrical resistivity of the carbon foam substrate and applying current to the catalyst element, the entire substrate can act as an electric heating element and shorten the time required to reach operational temperatures through variations of thermal properties. CFOAM Carbon Foam can also be designed as the shell that houses the catalyst elements further reducing cost and weight.

Among the R&D programs at Touchstone are the development of a new set of non-metallic designs utilizing a set of materials which were largely unavailable just a few years ago. The creation of non-metallic exhaust systems stemmed out of the development of new carbon foam at Touchstone made from coal, CFOAM, which was thought to be the answer to a new, high temperature core in composite sandwich structures. CFOAM carbon foam can be used indefinitely to about 650°F (343°C). Utilizing CFOAM carbon foam with ceramic matrix composites and polymer composites, Touchstone has developed a set of unique designs to handle the exhaust from internal combustion engines, and turbine engines.

The ceramic matrix composites Touchstone is utilizing will operate at temperatures up to 3600°F (2000°C) and the polymer composite systems will operate up to about 450°F (232°C). Lightweight, non-metallic exhaust systems can provide higher engine operating efficiencies, improved handling of high performance automobiles and boats, and opens the design envelope to manufacture designs difficult with typical metal designs. For example, imagine a composite cowling where the exhaust system is integral in the aerodynamic design of the engine cowling and where the shape of the exhaust can be designed without the preconceived notion that the exhaust system will always be circular in cross section. Touchstone has all the equipment and expertise to develop these non-metallic exhaust systems.

Down pipe with a stainless steel expansion connector, the down pipe is made of 409ss (**Image 4.9-6**).

**Image 4.9-6: Down Pipe**
*(Source: FEV, Inc. and A2mac1 data base)*

The muffler with tail pipe is made from aluminized steel (**Image 4.9-7**).

**Image 4.9-7: Muffler with Tail Pipe**
*(Source: A2mac1 data base)*

The Chevrolet Silverado's other technologies include EDPM hangers and welded hanger brackets (**Image 4.9-8**), and rubber hanger and car side hanger brackets (**Image 4.9-9**).

**Image 4.9-8: Pipe Side Hanger Brackets**
*(Source: FEV, Inc.)*

**Image 4.9-9: Rubber Hanger (left) and Car Side (right) Hanger Brackets**
*(Source: FEV, Inc. and A2mac1data base)*

**Image 4.9-10** shows a section view of the exhaust and the pipe as a whole without the crossover pipe.

**Image 4.9-10: Silverado Exhaust System**
*(Source: A2mac1 data base)*

### 4.9.1.3 Mass Reduction Industry Trends

Industry trends vary for exhaust systems, ranging from mild steel, titanium, special grades of stainless steel, and magnesium in race cars to low-production vehicles. There are many different types of stainless steel that can be considered for exhaust systems. The use of tailor-welded blanks of different types of stainless steel allows for thicker and thinner areas of stainless steel as needed. A common type is austenitic stainless such as 304. It is difficult to fabricate, however, owing to the rate of strain hardening. If very severe bending is required, it may be necessary to stress-relieve the material by annealing the pipe part of the way through the forming process. There are other stainless materials available in the 300 Series stainless family, but they are more brittle and have a poorer thermal shock performance than 409 Series stainless, which is most often used in today's OEM stainless systems. Although using 304 in place of 409ss allows for a thinner wall thickness thereby reducing weight. The down and cross over pipes thinning might cause an NVH issue and in this study the compounding of the engine size also reduced the exhaust size and may have alleviated the NVH issue and if not the study has added money in the total cost rollup to account for any unforeseen NVH issues.

While titanium is widely used for exhausts on motorcycles, the automotive industry has largely shunned this material, and for good reason: The bending stresses from forming titanium sheets requires extra supports to prevent cracking at high stress areas. Titanium's main advantage, however, is its low density: approximately 40% lower density than stainless steel. Since 2006, the use of titanium alloys for automotive exhaust systems manufacturing has increased for the high-end market vehicles. Titanium alloys used for exhaust system fabrication use additional alloying elements, as aluminum, copper, niobium, silicon, and iron. The addition of these elements significantly increases the oxidation resistance and mechanical properties of the alloy. **Image 4.9-11** shows a titanium exhaust system.

**Image 4.9-11: Titanium Exhaust System**
*(Source: Google Images)*

Some materials that are being considered for future applications are carbon fiber rap with high premature resins. Muffler shells are constructed using high-temp carbon fiber, stainless steel, titanium, or Inconel materials. Carbon fiber shells feature a two-twill pattern that is autoclaved to maintain precise spec and lasting durability. The 304 Series stainless steel shells are made from lightweight thin wall material. The aircraft grade titanium and Inconel shells are made from .023" wall material and are super lightweight. The motorcycle industry is currently using this technique, and will soon cross over into the high production automotive industry once the supply ramps up to bring the cost of carbon fiber down as shown in **Image 4.9-12.**

**Image 4.9-12: Carbon Fiber**
*(Source: Google Images)*

Other trends for exhaust systems include the use of different materials for the metal hanger brackets, such as the hollow stainless steel and titanium hanger brackets as shown in **Image 4.9-13.**

**Image 4.9-13: Hollow Hanger Brackets**
*(Source: Google Images)*

EDPM (or rubber) hangers are used by most OEMs today, including on the Chevrolet Silverado as shown in **Image 4.9-14.**

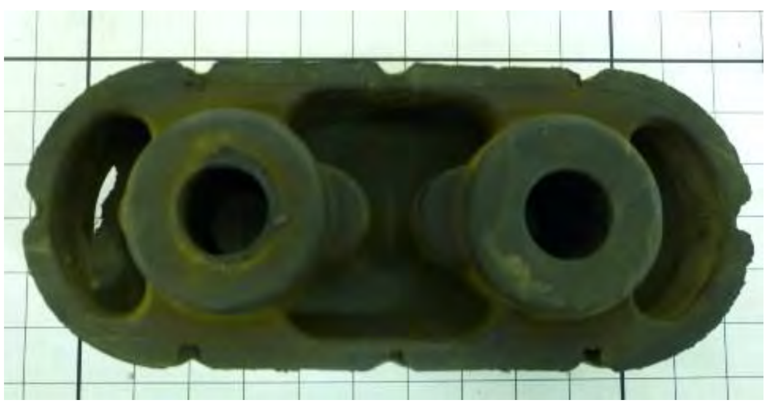


**Image 4.9-14: EDPM Hanger**
*(Source: FEV, Inc.)*

SGF® is a European automotive supplier of exhaust hangers. They have a patented process for adding cord inlay to the exhaust hangers that reduces weight and size. SGF exhaust hangers were also selected as a means of mass reduction. SGF hangers' advantages include:

- Weight reduction, up to 37% lighter than competitor's models.
- Very high load capacity in X, Y, and Z directions

- Reduce the number of hangers and hanger brackets
- Packaging: Due to becoming 40% more narrow, hangers can be positioned tight to the exhaust system
- Up to 21 times the life cycles of competitors' models
- Extreme durability, including high- and low-temperature performance
- The hangers do not need to be changed over the lifetime of the car
- High break load: 10 kN
- Use of EPDM instead of expensive silicon rubber
- Cord inlay for strength

Using the SGF hangers reduced the number of hangers and hanger brackets on the car side as well as the pipe side.

A recommendation by SGF to remove three hangers on the existing exhaust system would require the new hangers and brackets to be relocated, as **Figure 4.9-2** shows.

**Weight, Material, Dimension**

| | SGF LS000-E077-002  | Toyota 17565-0P041  |
|---|---|---|
| Weight and number of parts: | 45 grams/ 3pcs | 68 grams/ 6 pcs |
| Size (y-axis) | 25 mm | 34 mm |
| Material | EPDM | EPDM |
| Bolt diameter | 10mm | 12mm |

**Durability, Testing Conditions and Results**

| | SGF LS000-E077-002  | Toyota 17565-0P041  |
|---|---|---|
| 120ºC; Z=45N +- 180N | | Failed at 42000 cycles |
| 120ºC; Z=90N +- 360N | 4 Parts, stopped without any fault at 800000 cycles | Specimen No<br>1:Failed at 1600 cycles<br>2:Failed at 2379 cycles |
| | | |
| | | |

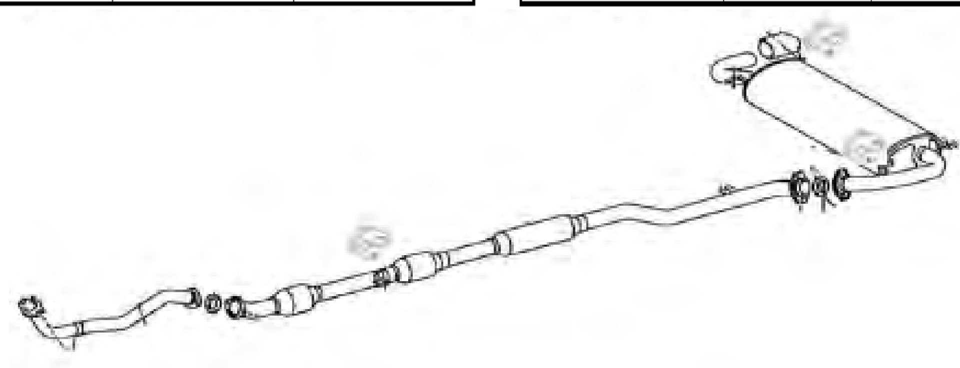


**Figure 4.9-2: SGF® Existing Exhaust System Recommendation (markings indicate location of hangers to be removed)**

*(Source: SGF)*

**Figure 4.9-3** shows an example of how the SGF hangers, which are smaller in size with more strength, result in an up to 37% lighter product. Note that the hanger strength comes from the cord inlay reinforcement.

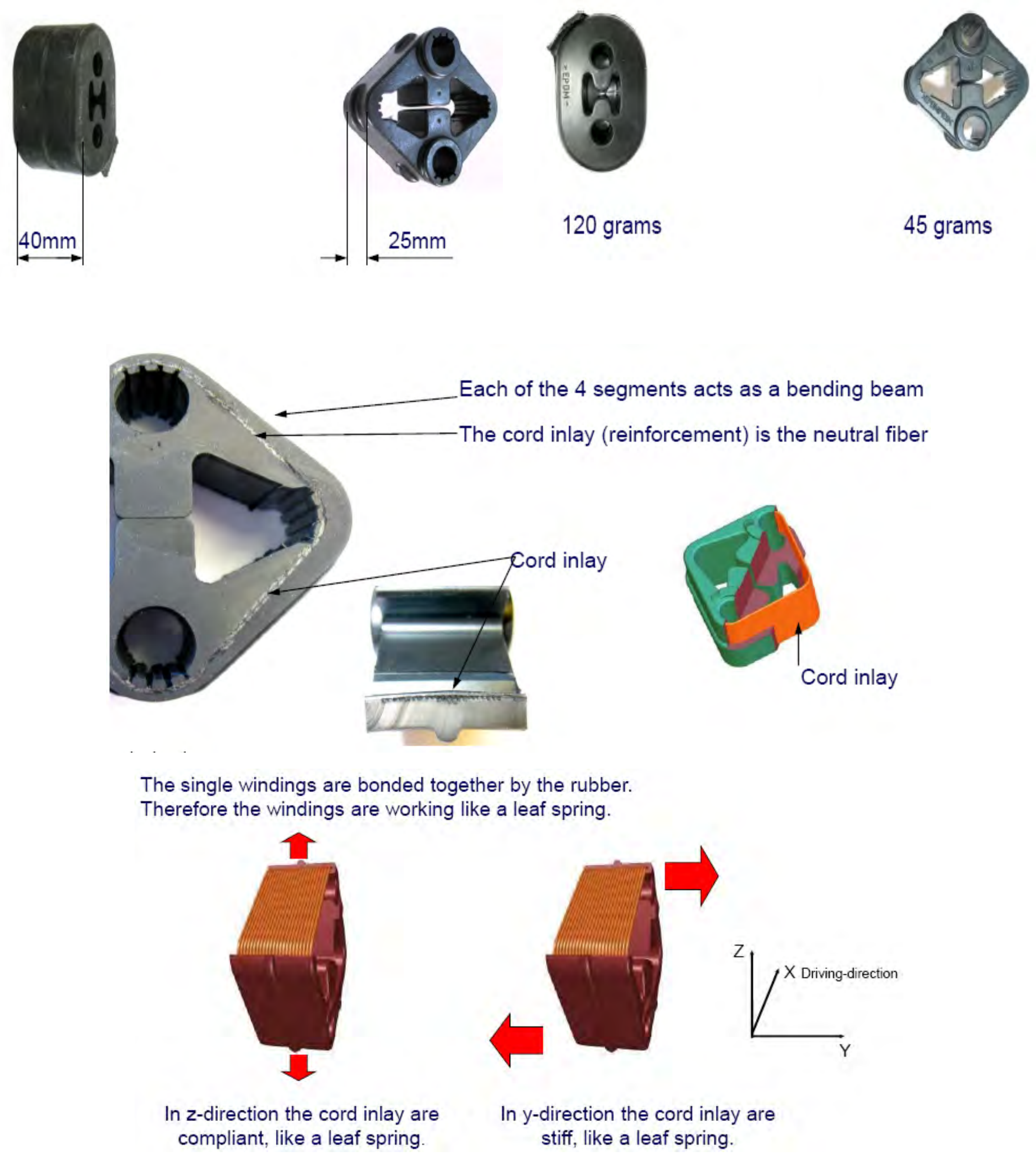



**Figure 4.9-3: SGF Hangers**
*(Source: Presentation material and information provided by SGF)*

### 4.9.1.4 Summary of Mass Reduction Concepts Considered

Ideas considered for the exhaust weight reduction were a titanium system, different types of stainless steels, Mubea TRT, hollow hangers and using optional materials for the exhaust rubber hanger grommets (**Table 4.9-4**).

**Table 4.9-4: Summary of Mass Reduction Concepts Initially Considered for the Exhaust System**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **Acoustic Control Components** | | | |
| Crossover pipe assy | Base cross pipe using TRB | 20% Mass Reduction | **Risk:** Cost increase<br>**Benefit:** Control over wall thicknesses, Lighter weight, |
| Crossover pipe assy | Base cross pipe reduce wall thickness from 1.9mm 409ss wall to 1.2mm 304ss ((Can't reduce pipe wall without going to 304ss)) | 34% Mass Reduction | **Risk:** Can't reduce pipe wall without going to 304ss<br>**Benefit:** Lighter weight, better impact resistance |
| Crossover pipe assy | Base 409SS to GR2 titanium alloy | 48% weight save & with big cost increase | **Risk:** Less impact resistance, Higher material cost, harder to weld<br>**Benefit:** Lighter weight |
| Crossover pipe assy | Base 409SS to GR2 titanium alloy, then reduce wall thickness from 1.6mm wall to 1.2mm | 64% weight save & with cost increase | **Risk:** Less impact resistance, Higher material cost, harder to weld<br>**Benefit:** Lighter weight, Control over wall thicknesses, |
| Down pipe assy | Base cross pipe using TRB | 20% Mass Reduction | **Risk:** Cost increase<br>**Benefit:** Control over wall thicknesses, Lighter weight, |
| Down pipe assy | Base down pipe reduce wall thickness from 1.9mm 409ss wall to 1.2mm 304ss ((Can't reduce pipe wall without going to 304ss)) | 34% Mass Reduction | **Risk:** Can't reduce pipe wall without going to 304ss<br>**Benefit:** Lighter weight, better impact resistance |
| Down pipe assy | Base 409SS to GR2 titanium alloy | 48% weight save & with big cost increase | **Risk:** Less impact resistance, Higher material cost, harder to weld<br>**Benefit:** Lighter weight |
| Down pipe assy | Base 409SS to GR2 titanium alloy, then reduce wall thickness from 1.6mm wall to 1.2mm | 64% weight save & with cost increase | **Risk:** Less impact resistance, Higher material cost, harder to weld<br>**Benefit:** Lighter weight, Control over wall thicknesses, |
| EDPM Exhaust hanger | SGF for rubber Hanger Isolators | 70% weight save & cost increase | **Risk:** None<br>**Benefit:** Cost increase, Lighter weight, better impact resistance, possiblity to use less qty |
| EDPM Exhaust hanger | Use Polyone foaming agent | 10% weight save & with Save | **Risk:** Manage foaming pellets and mixing<br>**Benefit:** Faster cycle time, Cost less, Lighter weight |
| Steel Exhaust hanger brkt | Hollow exhaust hangers and make 304SS | 29% weight save & cost save | **Risk:** Rust, Less impact resistance, harder to control welding<br>**Benefit:** Cost save, Lighter weight, |
| Muffler | Base grade Al/steel to 304SS | 3% weight save & cost increase | **Risk:** Big cost increase for little weight save<br>**Benefit:** Lighter weight, better impact resistance, stronger |
| Muffler | 304SS and go from 1.4mm wall to 1mm | 31% weight save & with big cost increase | **Risk:** Less impact resistance<br>**Benefit:** Cost less Lighter weight |
| Muffler | Base grade Al/steel to titanium alloy | 49% weight save & with cost increase | **Risk:** Less impact resistance, Higher material cost, harder to weld<br>**Benefit:** Lighter weight |
| Muffler | Titanium alloy and go from 1.4mm wall to 1mm | 63% weight save & with cost increase | **Risk:** Less impact resistance, Higher material cost, harder to weld<br>**Benefit:** Lighter weight, Control over wall thicknesses, |
| Muffler pipe | Base grade Al/steel to 304SS | 3% weight save & cost increase | **Risk:** Big cost increase for little weight save<br>**Benefit:** Lighter weight, better impact resistance, stronger |
| Muffler pipe | 304SS and go from 1.4mm wall to 1mm | 31% weight save & with big cost increase | **Risk:** Less impact resistance<br>**Benefit:** Cost less Lighter weight |
| Muffler pipe | Base grade Al/steel to titanium alloy | 49% weight save & with cost increase | **Risk:** Less impact resistance, Higher material cost, harder to weld<br>**Benefit:** Lighter weight |
| Muffler pipe | Titanium alloy and go from 1.4mm wall to 1mm | 63% weight save & with cost increase | **Risk:** Less impact resistance, Higher material cost, harder to weld<br>**Benefit:** Lighter weight, Control over wall thicknesses, |

### 4.9.1.5 Selection of Mass Reduction Ideas

**Table 4.9-5** includes the mass reduction ideas that were selected for the Exhaust System.

**Table 4.9-5: Mass Reduction Ideas Selected for Exhaust System**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| 09 | 00 | 00 | **Exhaust System** | |
| 09 | 01 | 01 | **Cross Over Pipe Assembly** | |
| | | | Cross Over Pipe Assembly | Base cross pipe reduce wall thickness from 1.9mm 409ss wall to 1.2mm 304ss ((Can't reduce pipe wall without going to 304ss)) |
| 09 | 01 | 02 | **Expantion clamp assy** | |
| | | | Down pipe to muffler | Base down pipe reduce wall thickness from 1.9mm 409ss wall to 1.2mm 304ss ((Can't reduce pipe wall without going to 304ss)) |
| | | | Steel hanger brkt | Hollow exhaust hangers and make 304SS |
| | | | Rubber hanger | SGF for rubber Hanger Isolators |
| 09 | 01 | 03 | **Muffler** | |
| | | | Muffler skin | Base grade Al/steel to 304SS & 304SS and go from 1.4mm wall to 1mm |
| | | | Steel hanger brkt | Hollow exhaust hangers and make 304SS |
| | | | Rubber hanger | SGF for rubber Hanger Isolators |

## 4.9.1.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.9-6** shows the weight and cost reductions per subsystem.

**Table 4.9-6: Sub-Subsystem Mass Reduction and Cost Impact for Acoustical Control Components Subsystem.**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| | | | | | | | | | |
| 09 | 00 | 00 | **Exhaust System** | | | | | | |
| 09 | 01 | 01 | Cross Over Pipe Assembly | A | 1.460 | $0.79 | $0.54 | 9.40% | 0.06% |
| 09 | 01 | 02 | Expantion clamp assy | C | 0.711 | -$1.09 | -$1.53 | 18.68% | 0.03% |
| 09 | 01 | 03 | Muffler | D | 4.169 | -$19.24 | -$4.61 | 21.91% | 0.17% |
| | | | | | | | | | |
| | | | | D | **6.340** (Decrease) | **-$19.54** (Increase) | **-$3.08** (Increase) | **16.52%** | **0.26%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

The secondary mass reduction was obtained by an overall 20% mass reduction of the vehicle and this affected the Exhaust System by a 3.5% reduction of the pipe and muffler pipe diameter of the exhaust.

The base Silverado exhaust system is made up of different pipe sections: the cross-over pipe assembly, down pipe to muffler, muffler, and the muffler pipe.

Since the vehicle was down sized by a 20% weight reduction which correlated into a reduction of the engine by 7.0%, this in turn reduced the exhaust systems pipe sections diameter by 3.5%

The reduction by downsizing is a .605 kg weight savings and a $5.85 cost decrease. This added to the base system weight savings equaled an overall weight savings of 6.95 kg and a cost increase of -$13.69.

### 4.9.2 Secondary Mass Reduction / Compounding

**Table 4.9-7** shows the secondary mass reduction and what the total reduction would be.

**Table 4.9-7: Calculated Subsystem Mass and Secondary Reduction and Cost Impact Results for Exhaust System.**

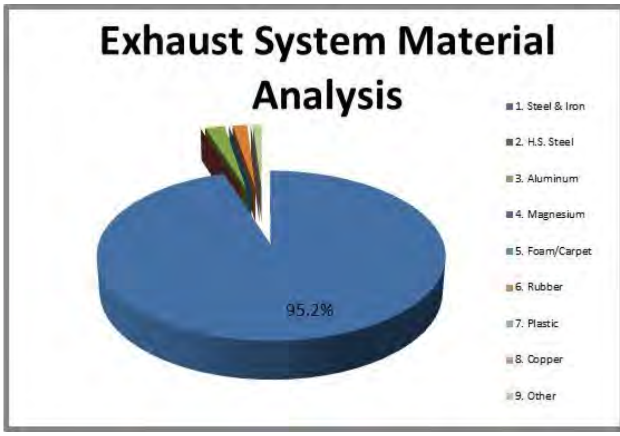
| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 09 | 00 | 00 | Exhaust System | | | | | | | | |
| 09 | 01 | 00 | Acoustical Control Components | 6.34 | 0.605 | 6.95 | -$19.54 | $5.85 | -$13.69 | -$1.97 | 0.28% |
| | | | | **6.34** (Decrease) | **0.605** (Decrease) | **6.95** (Decrease) | **-$19.54** (Increase) | **$5.85** (Decrease) | **-$13.69** (Increase) | **-$1.97** (Increase) | **0.28%** |

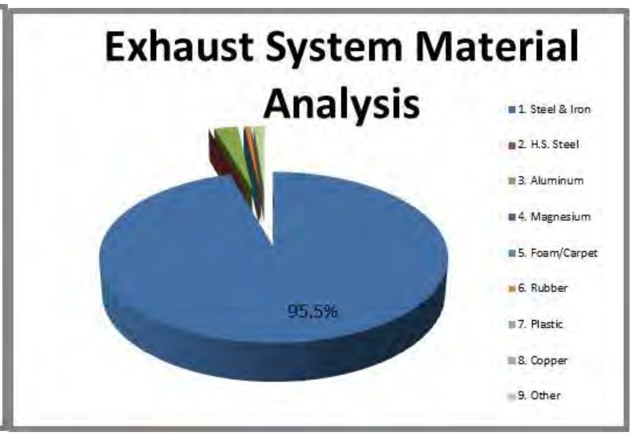
**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.9.3 Exhaust System Material Analysis

The charts in **Figure 4.9-4** show the weight reduction redistrubtion of the materials from the base exhaust materials to the new materials used in the study.

**Baseline Exhaust System** | **Total Exhaust System**




| | | Material Categories: |
|---|---|---|
| 95.2% | 36.514 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 2.2% | 0.841 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 1.7% | 0.636 | 6. Rubber |
| 0.0% | 0.000 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 1.0% | 0.379 | 9. Other |
| 100% | 38.370 | TOTAL |

| | | Material Categories: |
|---|---|---|
| 95.5% | 30.025 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 2.7% | 0.841 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.6% | 0.180 | 6. Rubber |
| 0.0% | 0.000 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 1.2% | 0.379 | 9. Other |
| 100% | 31.425 | TOTAL |

**Figure 4.9-4: Calculated Exhaust System Baseline Material and Total Material Content**

## 4.10 Fuel System

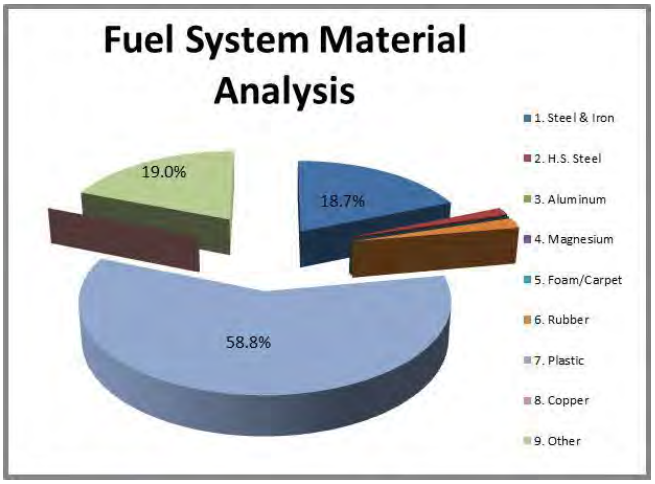
The Fuel System is combination of many items from the fuel filler system going into the fuel tank to the fuel pump, which delivers the fuel to the engine fuel injectors. There is also a fuel vapor management system that captures fuel vapors from the vehicle gas tank during refueling and running.

**Image 4.10-1: Silverado Fuel System**
*(Source: A2mac1)*

There are two subsystems in the Fuel System for the Chevrolet Silverado: the Fuel Tank and Lines Subsystem, and the Fuel Vapor Management Subsystem. Comparing these subsystems in **Table 4.10-1**, the Fuel Tank and Lines Subsystem was found to carry the greatest mass total of the two.

**Table 4.10-1: Baseline Subsystem Breakdown for Fuel System**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 10 | 00 | 00 | **Fuel System** | |
| 10 | 01 | 00 | Fuel Tank and Lines Subsystem | 22.598 |
| 10 | 02 | 00 | Fuel Vapor Management Subsystem | 3.742 |
| | | | | |
| | | | **Total System Mass =** | **26.340** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **System Mass Contribution Relative to Vehicle =** | **1.07%** |




| | | Material Categories: |
|---|---|---|
| 18.7% | 4.928 | 1. Steel & Iron |
| 1.5% | 0.396 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 2.0% | 0.531 | 6. Rubber |
| 58.8% | 15.489 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 19.0% | 4.997 | 9. Other |
| 100% | 26.340 | TOTAL |

**Figure 4.10-1: Calculated Material Content for the Fuel System Base BOM**

**Table 4.10-2** shows that, comparing the subsystems under the Fuel System, the greatest opportunity for mass reduction falls under the Fuel Vapor Management Subsystem. The calculated mass reduction results for the ideas generated related to the Fuel System. A mass savings of 1.61 kg was realized with a cost reduction of $3.25 which results in a cost savings of $2.02 per kg.

**Table 4.10-2: Calculated Mass Reduction and Cost Impact Results for Fuel System.**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys./ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 10 | 00 | 00 | Fuel System | | | | | | |
| 10 | 01 | 00 | Fuel Tank and Lines Subsystem | A | 0.731 | $2.36 | $3.23 | 3.23% | 0.03% |
| 10 | 02 | 00 | Fuel Vapor Management Subsystem | A | 0.876 | $0.89 | $1.02 | 23.42% | 0.04% |
| | | | | A | 1.607 (Decrease) | $3.25 (Decrease) | $2.02 (Decrease) | 6.10% | 0.07% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.10.1 Fuel Tank and Lines Subsystem

#### 4.10.1.1 Subsystem Content Overview

The Fuel Tank and Lines Subsystem is comprised primarily of the fuel tank and associated fuel lines between the fuel filler neck and cap to the fuel tank. The fuel lines between the fuel tank and fuel pump are also included in this subsystem.

**Image 4.10-2: Fuel Tank Assembly (Fuel Tank and Lines Subsystem)**
*(Source: A2mac1)*

**Table 4.10-3** shows the four sub-subsystems that make up The Fuel Tank and Lines Subsystem. The most significant contributor to the mass of this subsystem is the fuel tank assembly. This includes the tank, baffles, fuel pump, sending unit and exterior tank mounting brackets.

**Table 4.10-3: Mass Breakdown by Sub-subsystem for Fuel Tank and Lines Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 10 | 01 | 00 | Fuel Tank and Lines | |
| 10 | 01 | 01 | Fuel Tank Assy | 15.475 |
| 10 | 01 | 02 | Fuel Distribution | 5.090 |
| 10 | 01 | 03 | Fuel Filler (Refueling) | 0.912 |
| 10 | 01 | 04 | Fuel Tank Control Module (FTCM) | 1.121 |
| | | | Total Subsystem Mass = | 22.598 |
| | | | Total System Mass = | 26.340 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 85.80% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.92% |

#### 4.10.1.2 Chevrolet Silverado Baseline Technology

The Chevrolet Silverado Fuel System has some typical items that are found across many of today's vehicles; however, it also has some weight saving advantages built into the 2010 model already. For example some OEM's still manufacture steel tanks. The Silverado tank is made from a high-density polyethylene HDPE plastic to reduce weight, such as shown in **Image 4.10-3**.

**Image 4.10-3: Silverado Fuel Tank**
*(Source: FEV, Inc.)*

#### 4.10.1.3 Mass Reduction Industry Trends

4.10.1.3.1 <u>Fuel Tank</u>

Industry reports indicate more than 95% of the fuel tanks produced in Europe are made from plastics. Plastic tanks have become the primary material of choice in Europe and North America for many reasons:

1. A plastic tank system weighs two-thirds less than an average steel tank system. Advantages of the blow molding process used to make fuel tanks:
    a. Sheet polymer material for blow molding is high density polyethylene (HDPE), which has a lower density than water and is very chemically resistant.
    b. HDPE can be treated or laminated with barrier materials such as LLDPE which provides very effective emission control, rupture resistance, and extended temperature range.
    c. Tooling for blow molding is lower cost and is not stressed as heavily as tooling for steel parts.
    d. The main peripheral welded seam for the steel tank is eliminated with blow molding of HDPE. Components like filler necks can be welded to

the HDPE tank to seal and secure, and it will use much less energy than steel welding.

2. Plastics offer design flexibility for complex shapes, which are difficult to attain with steel. This includes integral connection features for attaching other fuel system components such as the vapor canister.

3. Impact and corrosion resistance is provided without secondary operations. No painting or coating is required.

Although not priced in our cost reduction estimates, life cycle total energy costs are also reduced using plastic:

- Plastic materials can be created and processed at lower temperatures than steel.
- Lower energy levels are required to recycle plastic than steel.

Regarding environmental concerns, feedstock for HDPE made from bio materials will be produced in at least one manufacturing plant (Braskem) which will help reduce our dependence on petroleum. Braskem is a Brazilian petrochemical company headquartered in São Paulo. The company is the largest petrochemical in the Americas by production capacity and the fifth largest in the world. By revenue it is the fourth largest in the Americas and the 17th in the world. *Some of this reference information was obtained through the internet.*

#### 4.10.1.3.2 Fuel Pump

Industry trends for the fuel pump (**Image 4.10-4)** to attach to the gas tank have been to remove the old two-piece stamping with interlocking and replace them with threads molded into the tank and a corresponding treaded cap as shown in **Image 4.10-5**.

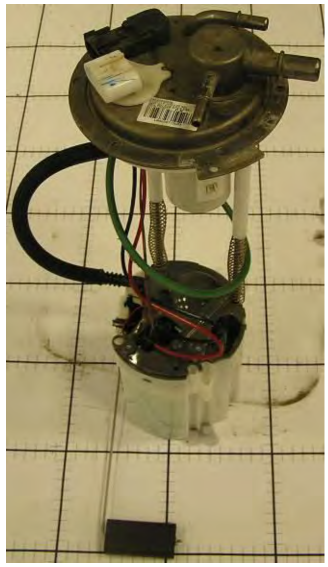


**Image 4.10-4: Fuel Pump**
*(Source: FEV, Inc.)*

**Image 4.10-5: Fuel Pump Mount Assembly (original at left; new at right)**
*(Source: A2mac1)*

#### 4.10.1.4 Summary of Mass reduction Concepts Considered

Brainstorming activities generated all of the ideas in **Table 4.10-4**. There are several suppliers and websites supporting the use of other components within the Fuel System.

**Table 4.10-4: Summary of Mass Reduction Concepts Initially considered for the Fuel Tank and Lines Subsystem.**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **Fuel Tank & Lines** | | | |
| Fuel Tank side - fuel pump ret. Ring | Remove ring and add POM to tank to make plastic ring for new POM (fuel pumping module retaining ring made out of POM to screw onto) | +32% Mass Increase ((Mass reduction seen in other subsystem)) | Added material to gas tank to make threaded lip, removed steel ring, cheap & easy to manufature |
| Fuel Tank side - fuel pump ret. Ring | Make out of Aluminium | Mass Reduction | Cost increase due to aluminum pricing, bigger due to added material for same strength |
| Fuel Tank side - fuel pump ret. Ring | Make out of Titanium | Mass Reduction | Cost increase due to titanium pricing, harder to manufacture |
| Fuel Tank side - fuel pump ret. Ring | Make out of Magnesium | Mass Reduction | Cost increase due to titanium pricing, harder to manufacture |
| Fuel Tank Shield-Bottom | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Fuel Tank Shield-Bottom | Use 3M glass bubbles | 6% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| Fuel Tank Shield-Bottom | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Fuel Line Bracket | Combo, plastic and PolyOne | 75% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture, can do class "A" surface, No added capital cost |
| Fuel Line Bracket | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Fuel Line Bracket | Use 3M glass bubbles | 6% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| Fuel Line Bracket | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Fuel Line Bracket | Make out of Aluminium | Mass Reduction | Cost increase due to aluminum pricing, bigger due to added material for same strength |
| Fuel Pumping Module | make the cover out of plastic (POM) | 57% Mass Reduction | Subject to plastic pricing, removed steel stampings and braze operations, cheap & easy to manufature |
| Fuel Pumping Module Ret. Ring | Make out of Aluminium | Mass Reduction | Cost increase due to aluminum pricing, bigger due to added material for same strength |
| Fuel Pumping Module Ret. Ring | Make out of Aluminium | Mass Reduction | Cost increase due to aluminum pricing, bigger due to added material for same strength |
| Fuel Pumping Module Ret. Ring | Make out of Titanium | Mass Reduction | Cost increase due to titanium pricing, harder to manufacture |
| Fuel Pumping Module Ret. Ring | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Fuel Pumping Module Ret. Ring | Use 3M glass bubbles | 6% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| Fuel Pumping Module Ret. Ring | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Fuel Pumping Module Ret. Ring | Remove, and combine with POM style fuel tank ring assy | 28% Mass Reduction | Remove ring and add POM to tank to make plastic ring for new POM (fuel pumping module retaining ring made out of POM to screw onto) |
| Fuel filler neck | Change to plastic | 38% Mass Reduction | Subject to plastic pricing, removed steel stampings and braze operations, cheap & easy to manufature |
| Fuel filler neck | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Fuel filler neck | Use 3M glass bubbles | 6.75% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| Fuel filler neck | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Fuel filler neck | Combo, plastic and PolyOne | 42% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture, can do class "A" surface, No added capital cost |
| Fuel filler Cap housing | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Fuel filler Cap housing | Use 3M glass bubbles | 8.55% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| Fuel filler Cap housing | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Fuel Cap | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Fuel Cap | Use 3M glass bubbles | 8.55% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| Fuel Cap | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Hose Clamps | Smaller width | 10% Mass Reduction | Cheaper, work just as well |

### 4.10.1.5 Selection of Mass Reduction Ideas

We chose most of the ideas generated from the brainstorming activities for detail evaluation as shown in **Table 4.10-5**.

**Table 4.10-5: Mass Reduction Ideas Selected for Fuel System Analysis**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **10** | **01** | **00** | **Fuel Tank & Lines** | |
| **10** | **01** | **01** | **Fuel Tank Assy** | |
| | | | Fuel Tank side - fuel pump ret. Ring | Remove ring and add POM to tank to make plastic ring for new POM (fuel pumping module retaining ring made out of POM to screw onto) |
| | | | Fuel Tank Shield-Bottom | Use Polyone foaming agent |
| **10** | **01** | **02** | **Fuel Distribution** | |
| | | | Fuel Line Bracket | Combo, plastic and PolyOne |
| | | | Fuel Pumping Module | make the cover out of plastic (POM) |
| | | | Fuel Pumping Module Retaining Ring | Remove, and combine with POM style fuel tank ring assy |
| **10** | **01** | **03** | **Fuel Filler (Refueling)** | |
| | | | Fuel filler neck | Combo, plastic and PolyOne |
| | | | Fuel filler Cap housing | Use Polyone foaming agent |
| | | | Fuel Cap | Use Polyone foaming agent |
| | | | Hose Clamps | Smaller width |

#### 4.10.1.5.1 Fuel pump and retaining ring Assembly

The solution chosen for the fuel pump and retaining ring assembly is to remove the retaining ring that is molded into the tank and to add material so that threads could be added to the tank side in place of the molded in steel ring. Also to make the top steel retaining ring out of plastic as shown in **Image 4.10-6**.

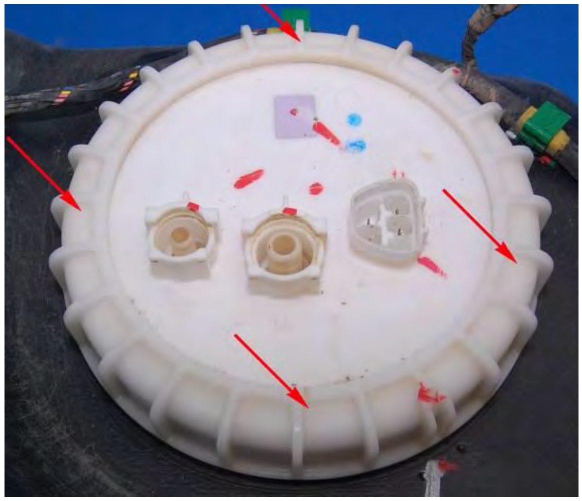


**Image 4.10-6: Fuel Pump and Retaining Ring Assembly**
*(Source: A2mac1)*

4.10.1.5.2 Fuel Tank Shield

The solution chosen to be implemented for the fuel tank shield is to use PolyOne® foaming agent (**Image 4.10-7**).

**Image 4.10-7: Plastic (HDPE) Fuel Tank**
*(Source: FEV, Inc.)*

4.10.1.5.3 Fuel pumping module cap

The solution chosen to be implemented for the fuel pumping module cap is to make it out of POM plastic as shown in **Image 4.10-8**. Instead of pinning the end of the strap, this design locks the strap end without the need of a pin.

**Image 4.10-8: Fuel Pumping Module Cap (original Silverado, left; POM plastic, right)**
*(Source: FEV, Inc., left ; and A2mac1 database, right)*

### 4.10.1.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.10-6** shows the results of the mass reduction ideas that were evaluated. This resulted in a subsystem overall mass savings of 0.730 kg and a cost savings differential of $2.36 for a system percentage of 3.23%.

**Table 4.10-6: Calculated Subsystem Mass Reduction and Cost Impact Results for Fuel Tank and Lines Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 10 | 01 | 00 | Fuel Tank and Lines | | | | | | |
| 10 | 01 | 01 | Fuel Tank Assy | A | 0.189 | $0.93 | $4.93 | 1.22% | 0.01% |
| 10 | 01 | 02 | Fuel Distribution | A | 0.372 | $1.30 | $3.50 | 7.31% | 0.02% |
| 10 | 01 | 03 | Fuel Filler (Refueling) | A | 0.170 | $0.13 | $0.74 | 18.59% | 0.01% |
| 10 | 01 | 04 | Fuel Tank Control Module (FTCM) | A | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | A | 0.731 (Decrease) | $2.36 (Decrease) | $3.23 (Decrease) | 3.23% | 0.03% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.10.2 Fuel Vapor Management Subsystem

#### 4.10.2.1 Subsystem Content Overview

The Fuel Vapor Management Subsystem is comprised of a charcoal/vapor canister and the connecting lines between the fuel tank and the charcoal canister. Also included in this is the vapor canister mounting bracket.

**Image 4.10-9: The Fuel Vapor Management Subsystem**
*(Source: A2mac1)*

**Table 4.10-7** shows the two sub-subsystems that make up the Fuel Vapor Management Subsystem. The most significant contributor to the mass of this subsystem is the fuel vapor canister assembly. This includes the canister and the mounting bracket.

**Table 4.10-7: Mass Breakdown by Sub-subsystem for the Fuel Vapor Management subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 10 | 02 | 00 | Fuel Vapor Management | |
| 10 | 02 | 01 | Fuel Vapor Canister | 2.828 |
| 10 | 02 | 02 | Purge Valve Assy | 0.914 |
| | | | Total Subsystem Mass = | 3.742 |
| | | | Total System Mass = | 26.340 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 14.20% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.15% |

#### 4.10.2.2 Silverado Baseline Technology

In the Chevrolet Silverado there is a steel-stamped mounting bracket for the vapor canister to the frame of the vehicle. Today, some vapor canisters are mounted to the gas tank or use a plastic mounting bracket.

#### 4.10.2.3 Mass Reduction Industry Trends

##### 4.10.2.3.1 Vapor Canister

Today's cleanest gasoline vehicles, certified to California's PZEV emission limits, require near-zero evaporative emissions and include additional technologies such as canister scrubbers to virtually eliminate bleed emissions from the carbon canisters during periods of low purge. Some vehicles also incorporate carbon-based air-intake HC traps to prevent engine breathing losses from escaping through the intake manifold and air induction system (AIS) after the engine is shut off.

Today, viable emission control technologies exist to reduce fuel system-based HC evaporative emissions from all types of spark-ignited engines including small handheld equipment up to large spark-ignited (LSI) vehicles. Applications include marine and recreational off-road vehicles. The major technologies that control permeation emissions include:

• Fuel tanks made of low permeation polymers

• Multilayer co-extruded hoses

• Low permeation seals and gaskets

Technologies designed to control diurnal, hot soak, and refueling HC emissions include:

- Advanced carbon canisters
- High working capacity activated carbon
- Honeycomb carbons scrubbers
- Air induction system (AIS) HC traps

Demands on vehicle manufacturers to achieve higher fuel efficiency through the use of smaller displacement, boosted engines and hybrid electric powertrains will create challenging operating conditions for evaporative emission control technologies. The lower purge volumes that result from smaller displacement engines or hybrid systems under partial or full electric drive will require the development of specialty carbon adsorbents and advanced canister designs to achieve the lowest evaporative emissions demanded by future regulations. Gasoline vehicles in other parts of the world and SI off-road equipment everywhere can benefit from much of the same technologies applied to passenger vehicles in the U.S. This paper will describe the types of technologies that are being used to meet the current and future evaporative emission regulations.[45]

#### 4.10.2.4 Summary of Mass Reduction Concepts Considered

Brainstorming activities generated all of the ideas in **Table 4.10-8**. There are several suppliers and websites supporting the use of other components within the Fuel System.

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45 *Source: Evaporative Emission Control Technologies for Gasoline Powered Vehicles December 2010, Manufacturers of Emission Controls Association*

**Table 4.10-8: Summary of Mass Reduction Concepts Initially Considered for The Fuel Vapor Management Subsystem.**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **Fuel Vapor Management** | | | |
| Vapor Canister | Normalize to 2013 Chevy Malibu Eco 2.4 | 15% Mass Reduction | Less weight, cost less |
| Vapor Canister | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Vapor Canister | Use 3M glass bubbles | 6% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| Vapor Canister | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Fuel Vapor Canister support on frame | Attach Vapor canister to fuel tank, remove canister Support on frame& on tank | 21% Mass Reduction | No stampings, no ecoat, no tooling |
| Purge valve Dust filter support | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Purge valve Dust filter support | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Purge valve Dust filter support | Use 3M glass bubbles | 6% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| Purge Line Bracket | Make out of Aluminium | Mass Reduction | Cost increase due to aluminum pricing, bigger due to added material for same strength |
| Purge Line Bracket | Make out of Aluminium | Mass Reduction | Cost increase due to aluminum pricing, bigger due to added material for same strength |
| Purge Line Bracket | Make out of Titanium | Mass Reduction | Cost increase due to titanium pricing, harder to manufacture |
| Purge Line Bracket | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Purge Line Bracket | Use 3M glass bubbles | 6% Mass Reduction | Density of glass is higher weight then foaming agent or gas products, has to be premixed with plastic resin, Handle with care, high cost |
| Purge Line Bracket | Combo, plastic and PolyOne | 30% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture, can do class "A" surface, No added capital cost |
| Purge Line Bracket | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |

### 4.10.2.5 Selection of Mass Reduction Ideas

We chose most of the ideas generated from the brainstorming activities for detail evaluation as shown in **Table 4.10-9**.

**Table 4.10-9: Mass Reduction Ideas Selected for the Fuel Vapor Management Subsystem.**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **10** | **02** | **00** | **Fuel Vapor Management** | |
| **10** | **02** | **01** | **Fuel Vapor Canister** | |
| | | | Vapor Canister | Normalize to 2013 Chevy Malibu Eco 2.4 |
| | | | Fuel Vapor Canister support on frame | Attach Vapor canister to fuel tank, remove canister Support on frame& on tank |
| **10** | **02** | **02** | **Purge Valve Assy** | |
| | | | Purge valve Dust filter support | Use Polyone foaming agent |
| | | | Purge Line Bracket | Combo, plastic and PolyOne |

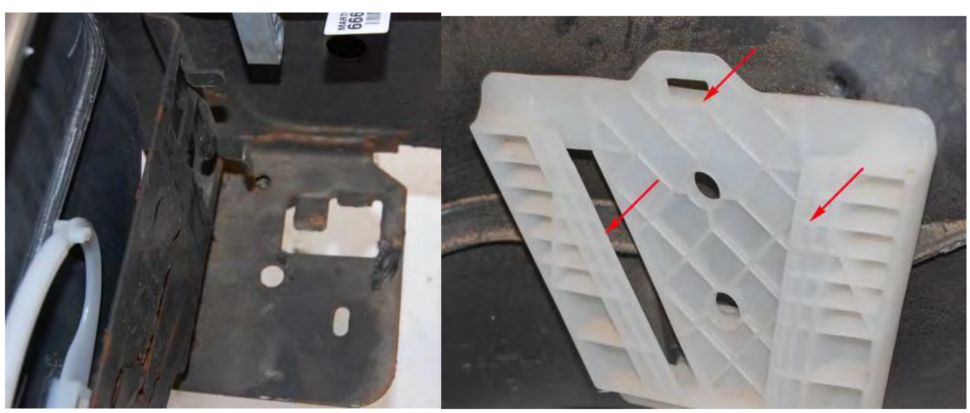
#### 4.10.2.5.1 Fuel Vapor Canister

The solution chosen to be implemented for the fuel vapor canister is to normalize the 2012 Chevrolet Malibu to the 2010 Chevrolet Silverado, as shown in **Image 4.10-10**.

**Image 4.10-10: Fuel Vapor Canisters**
**(Chevrolet Silverado, left; 2012 Chevrolet Malibu, right)**
*(Source: A2mac1, database)*

#### 4.10.2.5.2 Fuel Vapor Canister Support on Frame

The solution(s) chosen to be implemented for the Fuel Vapor Canister Support on Frame is to make it out of plastic and use the same design as the 2012 Chevrolet Malibu (**Image 4.10-11**).



**Orig. Silverado** **2012 Chevrolet Malibu**

**Image 4.10-11: Fuel Vapor Canister Support on Frame**
**(Chevrolet Silverado, left; 2012 Chevrolet Malibu, right)**
*(Source: FEV, Inc. and A2mac1, database)*

#### 4.10.2.6 Calculated Mass Reduction and Cost Impact Results

**Table 4.10-10** shows the results of the mass reduction ideas that were evaluated. This resulted in a subsystem overall mass savings of .876 kg and a cost savings differential of $0.89 for a system percentage of 23.42%

**Table 4.10-10: Calculated Subsystem Mass Reduction and Cost Impact Results for the Fuel Vapor Management Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Net Value of Mass Reduction Idea | | | | | |
| **10** | **02** | **00** | **Fuel Vapor Management** | | | | | | |
| 10 | 02 | 01 | Fuel Vapor Canister | A | 0.700 | $0.96 | $1.37 | 24.75% | 0.03% |
| 10 | 02 | 02 | Purge Valve Assy | B | 0.176 | -$0.07 | -$0.38 | 19.31% | 0.01% |
| | | | | **A** | **0.876** (Decrease) | **$0.89** (Decrease) | **$1.02** (Decrease) | **23.42%** | **0.04%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

The amount of plastic thast was used went up due to replacing the steel fuel vapor canister mounting bracket with a plastic one, and also replacing the two piece fuel pump mounting bracket with a one piece plastic one.

### 4.10.3 Secondary Mass Reduction / Compounding

The secondary mass reduction was obtained by an overall 20% mass reduction of the vehicle and this affected the Fuel System by a 7.0% reduction.

#### 4.10.3.1.1 Fuel reduction

The base Silverado holds 25.9 gallons of fuel; a reduction of 7.0% equals a 1.81 gallon reduction in fuel. One gallon of fuel weighs 2.75 kg by 1.81 reduction in fuel equals 4.99 kg overall mass reduction in fuel. 1.48 gallons at an average $3.55 cost of a gallon of gas equals $6.43 reduction without markup.

#### 4.10.3.1.2 Tank size reduction

The base Silverado holds 25.9 gallons of fuel and the tank weight is 10.6 kg, leaving a ratio of .410. With the new tank size only holding 24.1 gallons the ratio reduces the weight of the tank to 9.87 kg leaving an overall reduction of .743 kg.

.743 kg at $1.94 cost of HDPE equals $1.44 cost savings in plastic gas tank material without markup.

The overall reduction of the tank size and the fuel makes the total reduction 5.73 kg and $8.67 in cost with markup.

**Table 4.10-11** shows the secondary mass reduction and what the total reduction would be.

**Table 4.10-11: Calculated Subsystem Mass and Secondary Reduction and Cost Impact Results for Fuel System.**

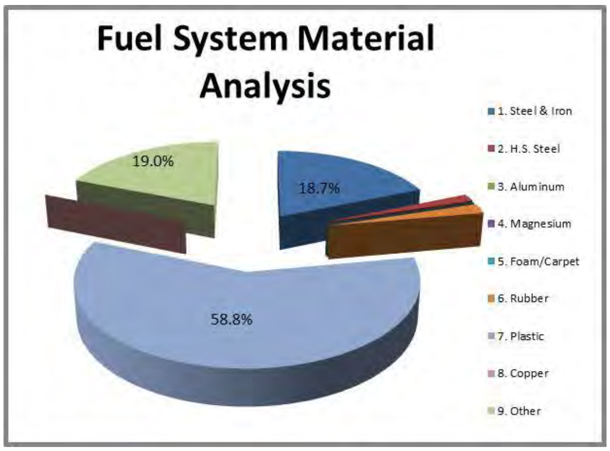
| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 10 | 00 | 00 | Fuel System | | | | | | | | |
| 10 | 01 | 00 | Fuel Tank and Lines Subsystem | 0.731 | 5.730 | 6.46 | $2.36 | $8.67 | $11.03 | $1.71 | 0.26% |
| 10 | 02 | 00 | Fuel Vapor Management Subsystem | 0.876 | 0.00 | 0.88 | $0.89 | $0.00 | $0.89 | $1.02 | 0.04% |
| | | | | 1.61 (Decrease) | 5.73 (Decrease) | 7.34 (Decrease) | $3.25 (Decrease) | $8.67 (Decrease) | $11.92 (Decrease) | $1.62 (Decrease) | 0.30% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.10.4 Fuel System Material Analysis

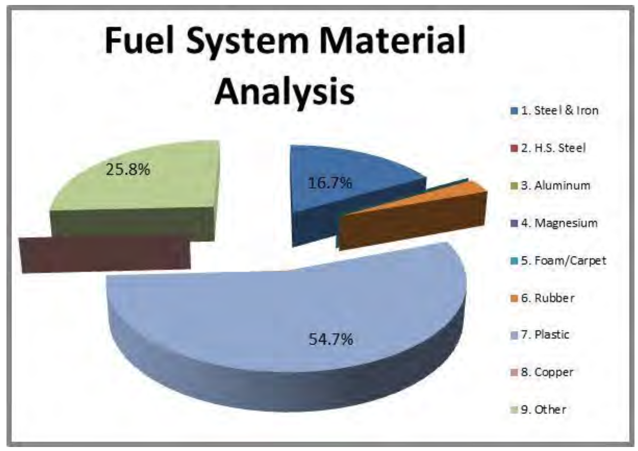
The Material Categories for the Baseline Fuel System and for the Total Mass Reduced Fuel System are shown in **Figure 4.10-2**. "Steel and Iron" decreased from 4.928 kg to 3.172 kg, and "Plastic" (due to the gas tank) decreased from 58.8% (15.489 kg) to 54.7% (10.394 kg). As can be seen, materials listed under "Other" increased in percentage of mass, from 19.0% to 25.8%.

**Baseline Fuel System**




| | | Material Categories: |
|---|---|---|
| 18.7% | 4.928 | 1. Steel & Iron |
| 1.5% | 0.396 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 2.0% | 0.531 | 6. Rubber |
| 58.8% | 15.489 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 19.0% | 4.997 | 9. Other |
| 100% | 26.340 | TOTAL |

**Total Fuel System**




| | | Material Categories: |
|---|---|---|
| 16.7% | 3.172 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 2.8% | 0.531 | 6. Rubber |
| 54.7% | 10.394 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 25.8% | 4.906 | 9. Other |
| 100% | 19.003 | TOTAL |

**Figure 4.10-2: Calculated Fuel System Baseline Material and Total Material Content**

## 4.11 Steering System

The Chevrolet Silverado uses a hydraulic power steering system. Representative power steering systems for cars and trucks supplement steering effort via an actuator (in the case of this study a hydraulic cylinder), which is part of a servo system. These systems have a direct mechanical connection between the steering wheel and the linkage that steers the front wheels. This means that a power steering system failure (to augment effort) still permits the vehicle to be steered using manual effort alone.

Other power steering systems (such as those in the largest off-road construction vehicles) have no direct mechanical connection to the steering linkage; they use electromechanically actuators. Systems of this kind, with no mechanical connection, are sometimes called “drive-by-wire” or “steer-by-wire.” In this context, “wire” refers to electrical cables that carry power and data, not thin-wire-rope mechanical control cables.

In electric power steering systems (EPS), electric motors provide the assistance instead of hydraulic systems. As with hydraulic types, power to the actuator (i.e., steering assist motor) is controlled by the rest of the power steering control system.

Included in the Steering System are the Steering Gear, Power Steering, Steering Equipment, and Steering Column Assembly Subsystems. The Steering Gear Subsystem is the largest weight contributing subsystem at 13.89 kg (as shown in **Table 4.11-1**).

**Table 4.11-1: Mass Breakdown by Subsystem for Steering System**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| **11** | **00** | **00** | **Steering System** | |
| 11 | 01 | 00 | Steering Gear | 13.893 |
| 11 | 02 | 00 | Power Steering Pump | 5.439 |
| 11 | 03 | 00 | Power Steering Equipment | 1.011 |
| 11 | 04 | 00 | Steering Column Assy | 12.171 |
| | | | | |
| | | | **Total System Mass =** | 32.514 |
| | | | **Total Vehicle Mass =** | 2454 |
| | | | **System Mass Contribution Relative to Vehicle =** | 1.32% |

**Image 4.11-1: Silverado Steering System**
*(Source: http://parts.nalleygmc.com/showAssembly.aspx?ukey_assembly=403923)*

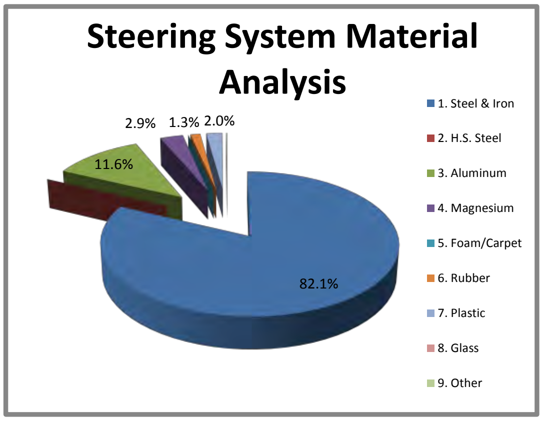
The Steering Gear, Steering Equipment, and Steering Column were used for mass reduction considerations. The Steering Pump Subsystem offered the greatest weight savings at 5.44 kg. (**Table 4.11-2**)

**Table 4.11-2: Mass Reduction and Cost Impact for Steering System**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys./ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 11 | 00 | 00 | Steering System | | | | | | |
| 11 | 01 | 00 | Steering Gear | | -1.467 | -$247.24 | $168.57 | -10.56% | -0.06% |
| 11 | 02 | 00 | Power Steering Pump | | 5.439 | $40.69 | $7.48 | 100.00% | 0.22% |
| 11 | 03 | 00 | Power Steering Equipment | | 1.011 | $54.32 | $53.73 | 100.00% | 0.04% |
| 11 | 04 | 00 | Steering Column Assy | | 3.474 | $4.76 | $1.37 | 28.54% | 0.14% |
| | | | | A | 8.457 (Increase) | -$147.46 (Increase) | -$17.44 (Decrease) | 26.01% | 0.14% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

**Baseline Steering System**




| | | Material Categories: |
|---|---|---|
| 82.1% | 26.688 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 11.6% | 3.761 | 3. Aluminum |
| 2.9% | 0.959 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 1.3% | 0.408 | 6. Rubber |
| 2.0% | 0.662 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.1% | 0.036 | 9. Other |
| 100% | 32.514 | TOTAL |

**Figure 4.11-1: Calculated material content for the Steering System base BOM**

## 4.11.1 Steering Gear Subsystem

### 4.11.1.1 Subsystem Content Overview

As shown in **Table 4.11-3**, included in the Steering System subsystems is the Steering Gear. The Silverado used in this study contained rack and pinion steering mechanisms, in which the steering wheel turns the pinion gear. The pinion moves the rack, which is a linear gear that meshes with the pinion, converting circular motion into linear motion along the transverse axis of the truck (i.e., side-to-side motion).

The rack and pinion design, as shown in **Image 4.11-2,** has the advantages of a large degree of feedback and direct steering "feel." A disadvantage is that it is not adjustable, so that when it does wear and develop lash, the only remedy is replacement. Power steering helps the driver steer by directing some power to assist in swiveling the steered road wheels about their steering axis. The assist cylinder is built around the rack in this vehicle.

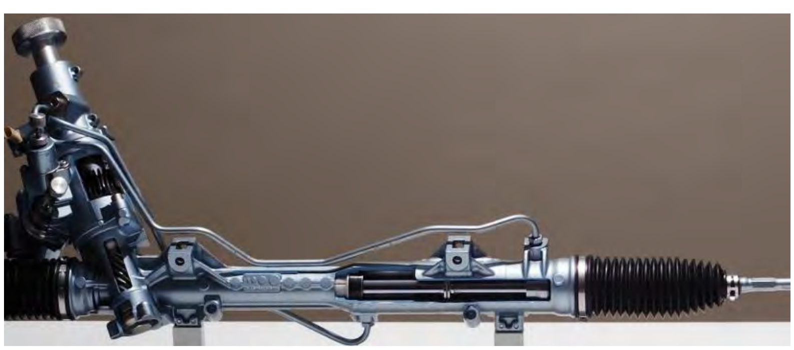


**Image 4.11-2: Silverado Rack and Pinion Steering Gear**
*(Source: A2mac1)*

**Table 4.11-3: Mass Breakdown by Sub-subsystem for Steering Gear Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 11 | 01 | 00 | Steering Gear Sub-System | |
| 11 | 01 | 01 | Steering Gear | 13.893 |
| | | | | |
| | | | Total System Mass = | 13.893 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 0.57% |

#### 4.11.1.2 Silverado Baseline Subsystem Technology

The Chevrolet Silverado uses a conventional hydraulic steering gear setup.

#### 4.11.1.3 Mass Reduction Industry Trends

The industry trend is electric assist in most vehicles and trucks with few exceptions. Electric power steering (EPS) is more efficient than the hydraulic power steering, since the electric power steering motor provides assistance only when the steering wheel is turned, whereas the hydraulic pump must run constantly. In EPS, the amount of assistance is easily tunable to the vehicle type, road speed, and even driver preference. In addition, electrical assistance is not lost when the engine fails or stalls, whereas hydraulic assistance stops working if the engine stops, making the steering doubly heavy as the driver must now turn not only the very heavy steering — without any help — but also the power-assistance system itself.

For the EPS-assisted rack-and-pinion to be a genuine success before it is eventually replaced by a true steer-by-wire systems, it needs to match what is considered the ultimate achievement in this car-design discipline: Provide an honest feel and feedback that gives drivers security in every condition of driving.

Autonomous driving is the next big step toward the ultimate goal of total accident avoidance. Vehicle technologies are quickly evolving, providing drivers with assistance in difficult traffic situations in traffic, improving highway and urban road safety, reducing fuel consumption and exhaust emissions, and all the while delivering a high degree of driving comfort. Autonomous cars have already been proven in normal traffic conditions, and there are valuable opinions as well about opening dedicated lanes or corridors for these vehicles.

### 4.11.1.4 Summary of Mass Reduction Concepts Considered

**Table 4.11-4** shows weight reductions taken for the Steering Gear Subsystem.

**Table 4.11-4: Summary of Mass Reduction Concepts Initially Considered for the Steering Gear Subsystem**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Steel Knuckle | Replace with Aluminum | 20% weight save | Low risk moderate cost increase |
| Steel Knuckle | Replace with Manesium | 30% weight save | Some risk moderate coat increase |
| Steel Tie Rod End | Replace with Aluminum | 20% weight save | Low risk moderate cost increase |
| Steel Tie Rod End | Replace with Manesium | 30% weight save | Some risk moderate coat increase |
| Steel Tie Rod Link | Replace with Aluminum | 20% weight save | Low risk moderate cost increase |
| Steel Tie Rod Link | Replace with Manesium | 30% weight save | Some risk moderate coat increase |
| Steering Gear | Repace Hydraulic with Electric | 10% weight save | No risk cost increase |

**Image 4.11-3: Silverado Steering Knuckle, Link, Tie Rod, and Steering Gear**
*(Source: A2mac1)*

#### 4.11.1.5 Selection of Mass Reduction Ideas

Another weight reduction opportunity for the subsystem steering gear was to shorten the tie rod ends and lengthen the threaded part of the tie rod ball joint. The current Chrysler minivan has a shorter tie rod end and it was used as a basis for this analysis, as detailed in **Table 4.11-5**. Using this, a 1%, 0.123 kg savings can result. Material selection of magnesium for some of the components also proved to be a means of weight reduction.

**Table 4.11-5: Mass Reduction Ideas Selected for the Steering Gear Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 11 | 01 | 00 | **Steering System** | |
| 11 | 01 | 01 | Steering Gear | Replaced with electric unit |
| 11 | 01 | 02 | Knuckle | Replace Steel Casting with Mg AJ62 (Mg-Al-Sr) |
| 11 | 01 | 03 | Tie rod end | Replace Steel Casting with Mg AJ62 (Mg-Al-Sr) |
| 11 | 01 | 04 | Tie rod link | Replace Steel Bar with Mg AJ62 (Mg-Al-Sr) |

#### 4.11.1.6 Mass Reduction and Cost Impact Estimates

**Table 4.11-6** shows the weight and cost reductions per Steering Gear Sub-subsystems.

**Table 4.11-6: Sub-Subsystem Mass Reduction and Cost Impact Estimates for Steering Gear Sub-Subsystem.**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 11 | 01 | 00 | **Steering Gear Sub-System** | | | | | | |
| 10 | 01 | 01 | Steering Gear | | -1.467 | -$247.24 | $168.57 | -10.56% | -0.06% |
| | | | | A | **-1.467** (Increase) | **-$247.24** (Increase) | **$168.57** (Decrease) | **-10.56%** | **-0.06%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.11.2 Power Steering Subsystem

### 4.11.2.1 Subsystem Content Overview

As shown in **Table 4.11-7**, included in the Power Steering Subsystem is the Power Steering Electronic Controls Sub-subsystem.

**Table 4.11-7: Mass Breakdown by Sub-subsystem for the Power Steering Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 11 | 02 | 00 | **Power Steering Pump** | |
| 11 | 02 | 01 | Power Steering Pump | 5.439 |
| | | | Total System Mass = | 5.439 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 0.22% |

### 4.11.2.2 Chevrolet Silverado Baseline Subsystem Technology

The Silverado uses an industry standard for its hydraulic pump in this system. It has a cast iron pump body with a steel oil reservoir (**Image 4.11-4**).

**Image 4.11-4: Silverado Hydraulic Pump and Reservoir**
*(Source: A2mac1)*

### 4.11.2.3 Mass Reduction Industry Trends

In this subsystem, the selection of an electrically assisted power steering system (EPS) is the latest technological trend. Replacing hydraulic assist with a computer-controlled electric motor seemed like a reasonable idea. Someday every car control will be by-wire; today's EPS appears to be a step in that direction. In the past decade of driving EPS-equipped cars, motorists found them to be lacking in feel and poorly tuned in comparison with the hydraulic-assist setups that have benefited from more than a half-century of development.

### 4.11.2.4 Summary of Mass Reduction Concepts Considered

For the Steering Pump Subsystem, the ideas in **Table 4.11-8** were reviewed.

**Table 4.11-8: Summary of Mass Reduction Concepts Initially considered for the Steering Pump Subsystem**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Hydraulic Pump | eliiminate | 100% weight save | no risk |
| Bracket | eliiminate | 100% weight save | no risk |
| Bolts, Nuts & Washers | eliiminate | 100% weight save | no risk |

### 4.11.2.5 Selection of Mass Reduction Ideas

The weight reduction solution for this subsystem was to eliminate the pump, steel mounting brackets, and all the bolts, nuts, and washers. **Table 4.11-9** shows using this resulted in a 100%, or a 5.44 kg weight savings.

**Table 4.11-9: Mass Reduction Ideas Selected for the Power Steering Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| **11** | **02** | **00** | **Power Steering Pump** | |
| 11 | 02 | 01 | Power Steering Pump | Replaced with electric unit |

#### 4.11.2.6 Mass reduction and Cost Impact Estimates

**Table 4.11-10** shows the weight and cost reductions for the Power Steering Pump Sub-subsystem.

**Table 4.11-10: Sub-Subsystem Mass Reduction and Cost Impact Estimates for Power Steering Pump Sub-Subsystem.**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| **11** | **02** | **00** | **Power Steering Pump** | | | | | | |
| 10 | 02 | 01 | Power Steering Pump | | 5.439 | $40.69 | $7.48 | 100% | 0.22% |
| | | | | A | **5.439** (Decrease) | **$40.69** (Decrease) | **$7.48** (Decrease) | **100.00%** | **0.22%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.11.3 Steering Equipment Subsystem

#### 4.11.3.1 Subsystem Content Overview

**Table 4.11-11** shows that included in the Power Steering Equipment Subsystem are the Power Steering Tube Assembly and Heat Exchange Assembly Sub-subsystems.

**Table 4.11-11: Mass Breakdown by Sub-subsystem for the Power Steering Equipment Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 11 | 03 | 00 | Power Steering Equipment | |
| 11 | 03 | 01 | Power Steering Tube Assembly | 0.650 |
| 11 | 03 | 02 | Heat Exchange Assy | 0.361 |
| | | | | |
| | | | Total System Mass = | 1.011 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 0.04% |

### 4.11.3.2 Chevrolet Silverado Subsystem Technology

The Silverado hydraulic system is pictured in

Image 4.11-5. The hydraulic tubes circulate the hydraulic pressure from the pump to the steering gear assist cylinder. The heat exchanger keeps the hydraulic oil at optimum running temperature for the system.

**Image 4.11-5: Silverado Hydraulic Equipment**
*(Source: http://parts.nalleygmc.com/showAssembly.aspx?ukey_assembly=403923)*

### 4.11.3.3 Mass Reduction Industry Trends

Industry mass reduction trends regarding the power steering system primarily eliminate the hydraulic system and go with electric equipment.

### 4.11.3.4 Summary of Mass Reduction Concepts Considered

Weight deductions were taken from the Steering Equipment Assembly Sub-subsystem, as shown in **Table 4.11-12.**

**Table 4.11-12: Summary of Mass Reduction concepts initially considered for the Steering Equipment Subsystem**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Hydraulic Tubes | eliiminate | 100% weight save | no risk |
| Heat Exchanger | eliiminate | 100% weight save | no risk |
| Bolts, Nuts & Washers | eliiminate | 100% weight save | no risk |

### 4.11.3.5 Selection of Mass Reduction Ideas

The weight reductions that were used for the Steering Equipment Subsystem are listed in **Table 4.11-13**.

**Table 4.11-13: Mass Reduction Ideas Selected for the Power Steering Equipment Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| 11 | 03 | 00 | **Power Steering Equipment** | |
| 11 | 03 | 01 | Power Steering Tube Assembly | Replaced with electric unit |
| 11 | 03 | 02 | Heat Exchange Assy | Replaced with electric unit |

#### 4.11.3.6 Mass Reduction and Cost Impact Estimates

**Table 4.11-14** shows a 5%, 1.15 kg total weight reduction for the sub-subsystem.

**Table 4.11-14: Sub-Subsystem Mass Reduction and Cost Impact Estimates for Power Steering Equipment Subsystem.**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 11 | 03 | 00 | Power Steering Equipment | | | | | | |
| 10 | 03 | 01 | Power Steering Tube Assembly | | 0.650 | $33.78 | $51.97 | 100% | 0.03% |
| 10 | 03 | 02 | Heat Exchange Assy | | 0.361 | $20.54 | $56.91 | 100% | 0.01% |
| | | | | A | 0.361 (Decrease) | $20.54 (Decrease) | $56.91 (Decrease) | 100.00% | 0.01% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.11.4 Steering Column Subsystem

#### 4.11.4.1 Subsystem Content Overview

Included in the Steering Column Subsystem are the Steering Column (and mounting brackets), Steering Wheel, and Column Cowl Sub-subsystems (**Table 4.11-15**).

**Table 4.11-15: Mass Breakdown by Sub-subsystem for the Steering Column Assembly Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 11 | 04 | 00 | Steering Column Assembly | |
| 11 | 04 | 01 | Steering column assy | 10.178 |
| 11 | 04 | 02 | Steering wheel assy | 1.781 |
| 11 | 04 | 03 | Column Cowl | 0.212 |
| | | | Total System Mass = | 12.171 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 0.50% |

### 4.11.4.2 Silverado Baseline Subsystem Technology

The Silverado has used the same column system for more than 10 years. There are opportunities in this subsystem that will allow for mass reduction without jeopardizing the system's safety aspects. Material selection will provide the advantage to produce tomorrow's technology in advanced plastics, magnesium, and composites.

**Image 4.11-6: Silverado Steering Column**
*(Source: http://parts.nalleygmc.com/showAssembly.aspx?ukey_assembly=403923)*

### 4.11.4.3 Mass Reduction Industry Trends

The 2009 Ford F-150 steering column is more than 60% magnesium based on volume, and represents a more than 40% weight savings over the prior model steering column. The steering column weight savings was realized through the integration of several components, such as brackets that must be attached by welding or bolting, into a single component. Specifically, the steel main tube and several brackets that were previously welded together, as well as an aluminum support casting that was bolted on, were integrated into a single magnesium die casting. Utilizing diecast magnesium also facilitated the integration of optional construction for the engineered steering column energy absorption features. This allowed Ford and Delphi Steering engineers to optimize the steering column's contribution to driver-side vehicle crash safety.

BAC Technologies Ltd.'s U.S. Patented carbon fiber driveshaft design is a mechanically integrated one-piece design in which the aluminum yokes are filament wound into the shaft. Wet composite material sinks into knurling on each yoke and encapsulates it during the manufacturing process. Therefore, each yoke is permanently locked into the shaft when the epoxy composite is cured. This design does not rely on adhesives to transfer the torsional load from the aluminum yoke to the carbon fiber composite. Independent laboratory tests have revealed BAC's carbon fiber driveshaft has significantly higher torsional strength and less weight over popular aluminum shafts and all other carbon composite driveshafts. This is a great application for the Silverado steering shafts.

Lexan EXL glass-filled polycarbonate-siloxane copolymer resin provides excellent stiffness and a high degree of impact over a very wide temperature range. SABIC Innovative Plastics has developed two designs: a two-part injection molded design with a leather wrap as a high-end solution and a one-piece injection-molded armature with a polyurethane over-molding. Both are attached to the steering column with a small metal hub. They have been shown to cut system costs by up to 20% and reduce mass by up to 40% compared to a magnesium or aluminum alloy steering wheel.

Downsizing and light weighting this system is just the beginning. By 2025 there will be vehicles in the market that will have no direct linkage between the wheel and the electric steering gear.

#### 4.11.4.4 Summary of Mass Reduction Concepts Considered

For the subsystem steering column, the ideas shown in **Table 4.11-16** were reviewed**.**

**Table 4.11-16: Summary of Mass Reduction Concepts Initially considered for the Steering System Subsystem**

| Component/ Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Shaft Mounting Tube | Steel tube to Aluminum Casting | 50% weight save | no risk minimum cost impact |
| Shaft Mounting Tube | Steel tube to Magnesium Casting | 60% weight save | low risk no cost impact |
| Shaft Mounting Tube | Steel tube to CCF Casting | 70% weight save | engineered solution no cost impact |
| Column Spindle | Steel bar to Aluminum | 50% weight save | no risk minimum cost impact |
| Column Spindle | Steel Bar to Magnesium | 60% weight save | low risk no cost impact |
| Column Spindle | Steel bar to CCF | 70% weight save | engineered solution no cost impact |
| Steering Wheel | Magnesium to Plastic | 25% weight save | no risk minimum cost impact |
| Steering Wheel | Magnesium to MMC | 10% weight save | low risk no cost impact |
| Steering Wheel | Magnesium to CCF | 35% weight save | engineered solution no cost impact |

### 4.11.4.5 Selection of Mass Reduction Ideas

The weight reductions that were used for the Steering Column Subsystem are listed in **Table 4.11-17**.

**Table 4.11-17: Mass Reduction Ideas Selected for the Steering Column Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| **11** | **04** | **00** | **Steering Column Assembly** | |
| 11 | 04 | 01 | Steering column assy | Replace Steel with Magnesiun |
| 11 | 04 | 02 | Steering Wheel Assy | Replace Magnesium with Plastic |
| 11 | 04 | 03 | Steering Column Cowl | Replace with PolyOne |

**Image 4.11-7: Steering Column Assembly, Steering Wheel Assembly, and Steering Column Cowl**
*(Source: A2mac1, except lower right FEV, Inc.)*

**Table 4.12 2: Mass Reduction and Cost Impact for the Steering Column System**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 11 | 04 | 00 | Steering Column Assembly | | | | | | |
| 10 | 04 | 01 | Steering column assy | | 3.248 | $0.09 | $0.03 | 31.91% | 0.13% |
| 10 | 04 | 02 | Steering wheel assy | | 0.204 | $4.34 | $21.22 | 11.47% | 0.01% |
| 10 | 04 | 03 | Column Cowl | | 0.021 | $0.34 | $15.84 | 10.00% | 0.00% |
| | | | | B | 3.474 (Decrease) | $4.76 (Decrease) | $1.37 (Decrease) | 28.54% | 0.14% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.11.5 Secondary Mass Reduction / Compounding

**Table 4.11-18** is a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This analysis recorded a system mass reduction of 8.46 kg (26.0%) at a cost increase of $147.46 ($17.44 per kg). The contribution of the steering system to the overall vehicle mass reduction is 0.35%. There are no compounding mass reductions for this system.

**Table 4.11-18: Sub-Subsystem Mass Reduction and Cost Impact Estimates for the Steering Equipment Subsystem**

| | | | | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 11 | 00 | 00 | Steering System | | | | | | | | |
| 11 | 01 | 00 | Steering Gear | -1.47 | 0.00 | -1.47 | -$247.24 | $0.00 | -$247.24 | $168.57 | -0.06% |
| 11 | 02 | 00 | Power Steering Pump | 5.44 | 0.00 | 5.44 | $40.69 | $0.00 | $40.69 | $7.48 | 0.22% |
| 11 | 03 | 00 | Power Steering Equipment | 1.01 | 0.00 | 1.01 | $54.32 | $0.00 | $54.32 | $53.73 | 0.04% |
| 11 | 04 | 00 | Steering Column Assy | 3.47 | 0.00 | 3.47 | $4.76 | $0.00 | $4.76 | $1.37 | 0.14% |
| | | | | 8.46 (Decrease) | 0.00 | 8.46 (Decrease) | -$147.46 (Increase) | $0.00 | -$147.46 (Increase) | -$17.44 (Increase) | 0.34% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

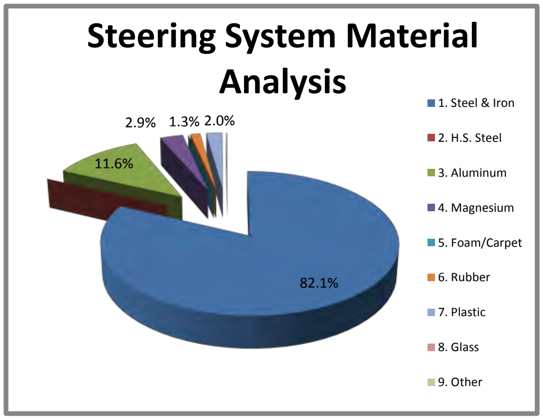
Secondary mass reduction was obtained by an overall 20% mass reduction of the vehicle and this affected some of the subsystems by a 5.0% to 7.0% reduction.

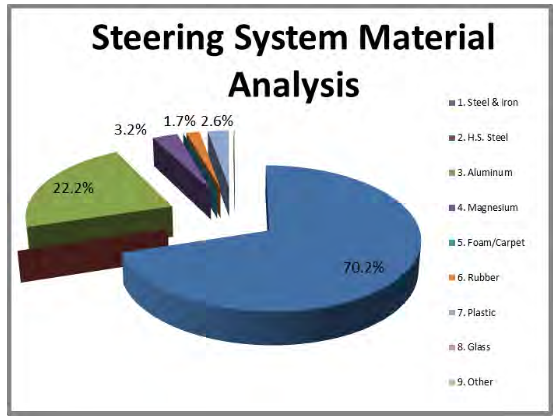
The Steering System considerations are that secondary mass reduction would not be viable. The assumed overall reduction of 20% on the total vehicle will not be equally distributed over the truck. That being said, a reduction of 10% over the front wheels will not allow the opportunity to remove more mass out of the system. We are confident with the direction that was taken on this system to improve it, reduce mass and removing more mass would compromise its integrity.

### 4.11.6 Steering System Material Analysis

A material breakdown for the base Steering System and for the light weighted and compounded Transmission System is provided in **Figure 4.11-2**. The "Steel & Iron" content category was reduced by almost 12%, while "Aluminum" and "Plastic" increased by 10.6% and 0.6%, respectively.

| Baseline Steering System | Total Steering System |
| --- | --- |




| | | Material Categories: |
| --- | --- | --- |
| 82.1% | 26.688 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 11.6% | 3.761 | 3. Aluminum |
| 2.9% | 0.959 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 1.3% | 0.408 | 6. Rubber |
| 2.0% | 0.662 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.1% | 0.036 | 9. Other |
| 100% | 32.514 | TOTAL |

| | | Material Categories: |
| --- | --- | --- |
| 70.2% | 16.881 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 22.2% | 5.337 | 3. Aluminum |
| 3.2% | 0.767 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 1.7% | 0.408 | 6. Rubber |
| 2.6% | 0.628 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 0.1% | 0.036 | 9. Other |
| 100% | 24.058 | TOTAL |

**Figure 4.11-2: Calculated Steering System Baseline Material and Total Material Content**

## 4.12 Climate Control System

The 2011 Chevrolet Silverado passenger cabin climate control application is representative of the typical current industry standard. The system provides comfort by maintaining desired cabin climate for the occupants. The level is selected using the control module, normally mounted in the instrument panel. The control system may vary slightly as the vehicle trim level changes.

The baseline mass breakdown of the Climate Control System into the four subsystems is displayed in **Table 4.12-1**. The Air Handling/Body Ventilation Subsystem accounts for more than 70% of the system mass.

**Table 4.12-1: Baseline for Climate Control System**

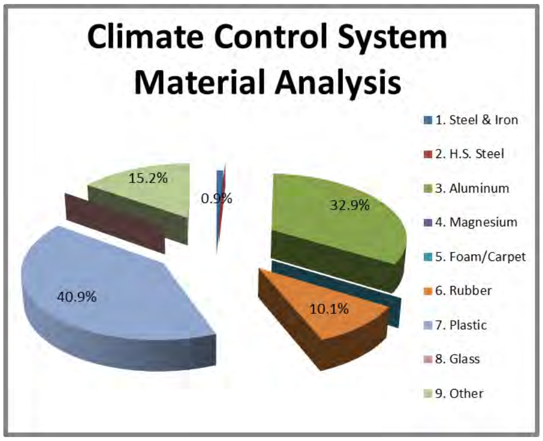
| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 12 | 00 | 00 | **Climate Control System** | |
| 12 | 01 | 00 | Air Handling / Body Ventilation Subsystemm | 14.881 |
| 12 | 02 | 00 | Heating / Defrosting Subsystem | 0.293 |
| 12 | 03 | 00 | Refrigeration / Air Conditioning Subsystem | 4.741 |
| 12 | 04 | 00 | Controls Subsystem | 0.394 |
| | | | **Total System Mass =** | **20.309** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **System Mass Contribution Relative to Vehicle =** | **0.83%** |

**Table 4.12-2** shows a total mass reduction of 1.94 kg from the entire Climate Control System with a cost saving of $14.71. The Air Handling/Body Ventilation Subsystem contributed all of the mass reduction for the Climate Control System. There were no mass reduction ideas applied to the Heating/Defrosting Subsystem, Refrigeration/Air Conditioning Subsystem, or the Controls Subsystem.

**Table 4.12-2: Mass Reduction and Cost Impact for the Climate Control System**

| | | | | Net Value of Mass-Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Estimated Mass Reduction "kg" (1) | Estimated Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | System/ Subsystem Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 12 | 00 | 00 | **Climate Control System** | | | | | | |
| 12 | 01 | 00 | Air Handling / Body Ventilation Subsystemm | A | 1.940 | $14.71 | $7.58 | 9.55% | 0.08% |
| 12 | 02 | 00 | Heating / Defrosting Subsystem | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 12 | 03 | 00 | Refrigeration / Air Conditioning Subsystem | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 12 | 04 | 00 | Controls Subsystem | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | **A** | **1.940** (Decrease) | **$14.71** (Decrease) | **$7.58** (Decrease) | **9.55%** | **0.08%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase




| | | Material Categories: |
|---|---|---|
| 0.9% | 0.182 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 32.9% | 6.686 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 10.1% | 2.052 | 6. Rubber |
| 40.9% | 8.310 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 15.2% | 3.079 | 9. Other |
| 100% | 20.309 | TOTAL |

**Figure 4.12-1: Calculated Climate Control System Baseline Material**

The pie chart in **Figure 4.12-1** details the material composition of the Climate Control Subsystem. It highlights the mass reduction achievement of 1.94 kg. The reduction effort is in the use of a newer amalgamation of plastic resins which, when processed, result in mass reduction.

#### 4.12.1.1 Subsystem Content Overview

The Climate Control System is primarily for occupant comfort while in the vehicle. It warms the cabin when the outside weather is cool, and cools the cabin when the outside weather is warm. It provides defrosting capabilities during the winter months to clear the windshield of any ice. It also removes moisture from the cabin which may cause the windows to “fog” when there is high humidity. The system receives outside air and conditions it according to the selected occupant comfort level. There is a heating coil within the main HVAC unit which circulates warm liquid from the engine cooling system through a series of hoses and piping connections. There is a cooling coil as well, chilled by a cooling agent circulated by the air conditioning compressor.

#### 4.12.1.2 Chevrolet Silverado Baseline Climate Control System Technology

The Climate Control System has four different subsystems as shown in **Table 4.12-1**. The majority of the system mass (73%) is contained within the Air Handling/Body Ventilation Subsystem. The main HVAC unit is the primary contributor to mass in this subsystem (81%).

The main HVAC unit contains all of the blower motors, air directional flaps and the motors which control these features. Additionally this unit contains the mass for the aluminum main heating coil and the aluminum main cooling coil in the assembled state.

In breaking this mass down, the Air Distribution Duct Components Sub-subsystem, which contains air distribution duct work and mounting hardware accounts for 2.89 kg, 19.4% of the total subsystem mass. The main HVAC Unit weighs in 11.996 kg (80.6% of the total subsystem mass), and 59.1% of the entire Climate Control Subsystem.

### 4.12.2 Air Handling / Body Ventilation Subsystem

#### 4.12.2.1 Subsystem Content Overview

**Table 4.12-3: Mass Breakdown by Sub-Subsystem for the Air Handling / Body Ventilation Subsystem Components Sub Subsystem**

| System | Subsystem | Sub-Subsystem | Description | System/ Subsystem Mass "kg" |
|---|---|---|---|---|
| **12** | **01** | **00** | Air Handling / Body Ventilation Subsystem | |
| 12 | 01 | 02 | Air Distribution Duct Components | 2.881 |
| 12 | 01 | 03 | Body Air Outlets | 0.000 |
| 12 | 01 | 04 | HVAC Main Unit | 11.996 |
| | | | | |
| | | | **Total Subsystem Mass =** | **14.877** |
| | | | **Total System Mass =** | **20.309** |
| | | | **Total Vehicle Mass =** | **2454** |
| | | | **System Mass Contribution Relative to System Mass =** | **73.25%** |
| | | | **System Mass Contribution Relative to Vehicle Mass =** | **0.83%** |

#### 4.12.2.2 Chevrolet Silverado Baseline Climate Control Subsystem Technology

The Air Handling / Body Ventilation Subsystem had a total mass of 14.881 kg. This mass does include the heating and air conditioning coils mounted in the main HVAC Unit. It also includes the motors and mounting hardware for all of the flap and gates which control the distribution of the conditioned cabin air. There was no mass reduction generated from these included components.

The heart of the Climate Control System is the main HVAC Unit and it provides 81% of the subsystem base mass. **Image 4.12-1** is the main HVAC Unit.

**Image 4.12-1: 2011 Chevrolet Silverado Main HVAC Unit**
*(Source: FEV, Inc. photo)*

The remainder of Chevrolet Silverado Climate Control System mass is duct work and mechanical structures. These are predominantly made from high density polyethylene (HDPE). The process is a very common industry process for these types of components. The strategy for mass reduction for the Chevrolet Silverado is to use replacement materials which meet the OEM climate control requirements for occupant comfort and operation safety.

Some of the components of the Climate Control System are structural in nature. In the main HVAC Unit there is a large amount of mechanical devices which require structural support to operate in the manner intended. In the Main HVAC Unit there are flaps used to direct the flow of conditioned air to various cabin locations. These are motor driven in most cases and therefore require additional structural integrity to properly support these motors and maintain proper system operation.

The main HVAC Unit also houses the heating coil and the cooling coil, and these coils require structural stability of the mounting component to maintain intended operational integrity.

#### 4.12.2.3 Mass Reduction Industry Trends

The field of plastics is continuously expanding the products they are creating as well as the applications they feel can transition from alternate products to plastics. Every day a new material is created, a new application developed, and a new customer will arrive on the scene looking for a technological advantage in his market segment.

The structural needs of Climate Control components allow for a wide range of change. With most of the components of the Climate Control System being hidden from view, they do not have to be appealing to the eye: they just have to function efficiently. For these reasons, a low-cost material is usually the fabric of choice everything else being equal. New processes are being developed to allow for lower costs, faster rates of production, and less material being used.

Our research looked at replacement materials which would meet the requirements of OEMs and reduce overall mass. Mucell processed foam was one of the products investigated, and Azote from Zotefoam, Inc. was another.

The Mucell process imparts an approximate 10% mass reduction opportunity on the component compared to HDPE types of traditional materials. The Zotefoam, Inc. process can yield a 50% - 80% mass reduction based on the product and application.

## Mucell®

The MuCell process can be used to produce components of less mass through a density change of the material which the MuCell process creates. The Mucell process has the opportunity to produce components which are 10-30% less in mass, yet do not exhibit any loss of mechanical properties.

Mass reduction is just one of the advantages the Mucell process provides. The mass reduction is generated by the creation of a foam-like product. The Mucell process injects a tightly controlled gas into the mold. Improved quality characteristics are realized due to the uniform stress patterns related to molding of the component.

In concert with the quality improvements there is an inherent productivity improvement directly linked to the efficiencies of the process gains realized as a result of the new process. The increased productivity of 20-30% per machine is a major gain. Another opportunity for the manufacturing process is to use the less dense material and employ lower tonnage machines to make the same part. This change will positively affect the cost of the components.

## Zotefoam, Inc. – Azote

For applications which do not require the structural stability of the Mucell replacement there is a product, Azote, from Zotefoams, Inc. Zotefoams has a unique manufacturing process for mass reduction of current plastic products. This product is currently used in climate control air ducts among other applications. The advantage this material has over other products is lower density and variety of applications which can use this due to the wide density numbers it can support.

**Image 4.12-2: Example of a Zotefoam under IP air duct**
*(Source: FEV, Inc.)*

Depending on the grade, high-density polyethylene (HDPE) Zotefoam can have a density range between 0.03 to - .115 g/cm$^3$. The density of regular HDPE is .95 g/cm$^3$. In instances where the base product is a standard density HDPE and a change to the Zotefoam process was introduced, the realized mass reduction would easily be 75% mass reduction.

**Image 4.12-3: Close up view of the Zotefoam under IP Air Duct**
*(Source: FEV, Inc.)*

The process for this product is known as twin sheet molding. The use of heat and air pressure is integral to the successful application of the technology.

The process is one sheet atop another. The sheets are introduced to the mold fixture, heat is applied, closely followed by air pressure allowing the individual sheets to form themselves into the mold tooling. Once the forming process is completed the edges of the form are welded together, forming a one-piece molded component.

**Image 4.12-4: Toyota Venza IP Air Duct (HDPE)**
*(Source: FEV, Inc.)*

**Image 4.12-5: Chevrolet Silverado IP Air Duct (HDPE)**
*(Source: FEV, Inc.)*

### 4.12.3 Summary of Mass reduction Concepts Considered

#### 4.12.3.1 Selection of Mass Reduction Ideas

**Table 4.12-4** Illustrates the concepts which were reviewed and applied to proper applications for mass reduction opportunities in the Climate Control System.

**Table 4.12-4: Summary of Mass Reduction Concepts Considered for the Climate Control System**

| Component / Assembly | Mass- Reduction Idea | Estimated Impact | Risks & Trade-Offs and/or Benefits |
|---|---|---|---|
| HVAC Ducts | Zotefoams' Azote Foam | 50% - 80%<br>Mass- Reduction | Moderate cost save depending on application. Currently used for passenger air ducts on the Boeing 787 Dream Liner. |
| Main HVAC Unit Housings and Flaps | Mucell Process | 10% Mass-Reduction | Low Cost.<br>Mucell used in high volume volume production applications, similar to the Silverado Climate Control System, for many OEMS. |

#### 4.12.3.2 Selection of Mass Reduction Ideas

**Table 4.12-5** displays the mass reduction ideas which were selected for the Climate Control System.

**Table 4.12-5: Mass Reduction Ideas Selected for the Climate Control System**

| System | Subsystem | Sub-Subsystem | Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **12** | **00** | **00** | **Climate Control System** | |
| 12 | 01 | 00 | Air Handling / Body Ventilation Subsystemm | |
| 12 | 01 | 02 | Air Distribution Duct Components (Duct Manifolds) | Zotefoam's Azote Material and process to replace HDPE blow molded Duct Manifolds. |
| 12 | 01 | 04 | HVAC Main Unit | MuCell process applied to applicable housings and flaps. |
| | | | | |

### 4.12.4 Secondary Mass Reduction / Compounding

The Climate Control Subsystem contributed a system mass reduction of 1.94 kg, (9.55%). This mass reduction provided a vehicle cost saving of $14.71, which equated to $7.59 per kg. The overall vehicle mass reduction contribution is 0.08%. **Table 4.12-6** is a summary of the calculated mass reduction and cost impact for each vehicle subsystem evaluated. There are no compounding mass reductions for this system.

#### 4.12.4.1 Mass-Reduction and Cost Impact

**Table 4.12-6** presents the mass and cost results for the lightweighting effort per system.

**Table 4.12-6: System Mass Reduction and Cost Impact for the Climate Control System**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 00 | 00 | Climate Control System | | | | | | | | |
| 12 | 01 | 00 | Air Handling / Body Ventilation Subsystemm | 1.94 | 0.00 | 1.94 | $14.71 | $0.00 | $14.71 | $7.59 | 0.08% |
| 12 | 02 | 00 | Heating / Defrosting Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 12 | 03 | 00 | Refrigeration / Air Conditioning Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| 12 | 04 | 00 | Controls Subsystem | 0.00 | 0.00 | 0.00 | $0.00 | $0.00 | $0.00 | $0.00 | 0.00% |
| | | | | 1.94 (Decrease) | 0.00 | 1.94 (Decrease) | $14.71 (Decrease) | $0.00 | $14.71 (Decrease) | $7.59 (Decrease) | 0.08% |

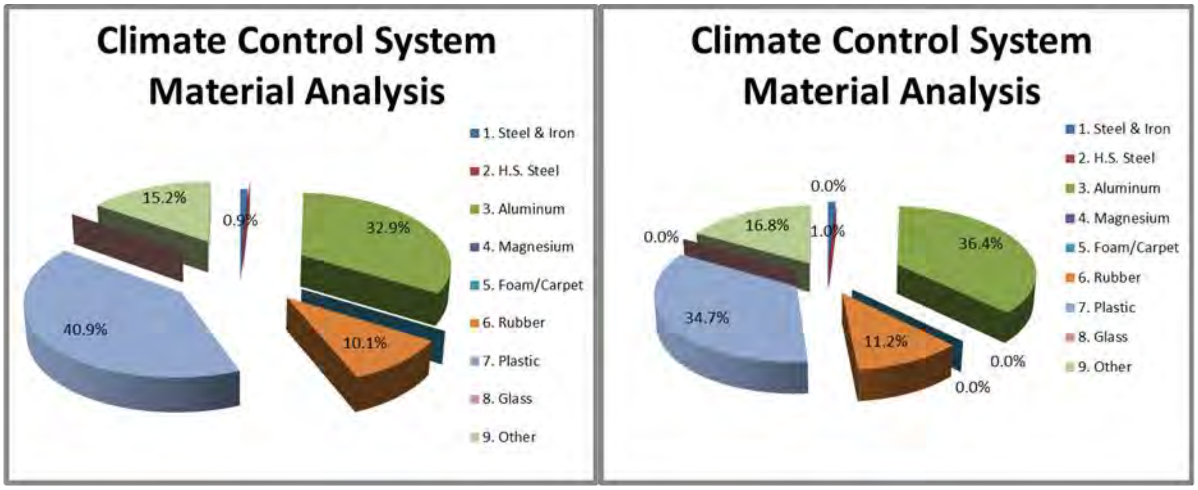
(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

**Table 4.12-6** shows the total mass reduction in the Climate Control System to be 1.94 kg with an associated cost savings of $14.71. This mass reduction was all contained in the Air Handling / Body Ventilation Subsystem.

### 4.12.5 Climate Control System Material Analysis

A material breakdown for the base Climate Control System and for the light weighted and compounded Transmission System is provided in **Figure 4.12-2**. The “Plastic” content category was reduced by 6.2%, while “Aluminum” and “Rubber” increased by 3.5% and 1.1%, respectively.

**Baseline Climate Control System** | **Total Climate Control System**




Baseline:

| | | Material Categories: |
|---|---|---|
| 0.9% | 0.182 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 32.9% | 6.686 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 10.1% | 2.052 | 6. Rubber |
| 40.9% | 8.310 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 15.2% | 3.079 | 9. Other |
| 100% | 20.309 | TOTAL |

Total:

| | | Material Categories: |
|---|---|---|
| 1.0% | 0.182 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 36.4% | 6.686 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 11.2% | 2.052 | 6. Rubber |
| 34.7% | 6.371 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 16.8% | 3.080 | 9. Other |
| 100% | 18.370 | TOTAL |

**Figure 4.12-2: Calculated Climate Control System Baseline Material and Total Material Content**

Percentage variance from Base BOM to New BOM are directly attributed to the change in the plastic material mass which affects all of the remaining assembly components.

## 4.13 Info, Gage, and Warning Device Systems

The Info, Gage, and Warning Device System includes two subsystems: Driver Information Module (instrument cluster) and Traffic Horns (Electric). The Instrument Cluster and Horn Subsystems weight are presented in **Table 4.13-1**, which shows the Instrument Cluster Subsystem is the greatest weight contributor in this system. Note: the horn subsystem includes the horn mechanism itself and not the components used to activate the horn in the steering wheel, which are in the Steering Subsystem.

**Table 4.13-1: Baseline Subsystem Breakdown for Info, Gage and Warning Device System**

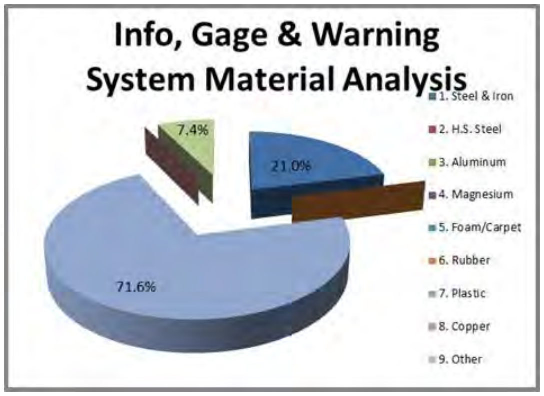
| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 13 | 00 | 00 | Info,Gage and Warning system | |
| 13 | 01 | 00 | Driver Information Module (Instrument Cluster) | 1.060 |
| 13 | 02 | 00 | Traffic Horns (Electric) | 0.518 |
| | | | Total System Mass = | 1.578 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 0.06% |

**Table 4.13-2** shows, the weight reduction results that were applied to the Info, Gage and Warning System. The ideas reduced the system weight by 0.248 kg which is a 15.72% system mass reduction.

**Table 4.13-2: Preliminary Mass Reduction and Cost Impact for the Info, Gage, and Warning Device System**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 13 | 01 | 00 | Info,Gage and Warning system | | | | | | |
| 13 | 01 | 01 | Drivers Info Center | A | 0.064 | $0.49 | $7.67 | 5.99% | 0.00% |
| 13 | 02 | 01 | Traffic Horn Assembly - LH | A | 0.092 | $0.09 | $0.93 | 35.64% | 0.00% |
| 13 | 02 | 02 | Traffic Horn Assembly - RH | A | 0.092 | $0.09 | $0.93 | 35.64% | 0.00% |
| | | | | A | 0.248 (Decrease) | $0.66 (Decrease) | $2.66 (Decrease) | 15.72% | 0.01% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase




| | | Material Categories: |
|---|---|---|
| 21.0% | 0.332 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 71.6% | 1.130 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper |
| 7.4% | 0.116 | 9. Other |
| 100% | 1.578 | TOTAL |

**Figure 4.13-1: Calculated material content for the Info, Gage, and Warning Device System Base BOM**

### 4.13.1 Instrument Cluster Subsystem

#### 4.13.1.1 Subsystem Content Overview

The Driver's Info Center Sub-subsystem is within the Driver Information Module (instrument cluster) Subsystem. The Traffic Horn Assembly (LH) and (RH) Sub-subsystems are part of the Traffic Horn (Electric) Subsystem.

**Image 4.13-1: Driver Information Module (instrument cluster)**
*(Source: Google Images)*

As seen in **Table 4.13-3**, the most significant contributor to the mass of the Info, Gage, and Warning subsystems 1.06 kg is the Driver's Info Center. This includes the cluster mask assembly, the cluster rear housing and the display housing.

**Table 4.13-3: Mass Breakdown by Sub-subsystems**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 13 | 01 | 00 | Info,Gage and Warning system | |
| 13 | 01 | 01 | Drivers Info Center | 1.060 |
| 13 | 01 | 01 | Traffic Horn Assembly - LH | 0.259 |
| 13 | 02 | 01 | Traffic Horn Assembly - RH | 0.259 |
| | | | | |
| | | | Total Subsystem Mass = | 1.578 |
| | | | Total System Mass = | 1.578 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 100.00% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.06% |

#### 4.13.1.2 Chevrolet Silverado Baseline Subsystem Technology

The Driver Information Module (instrument cluster) Subsystem follows the industry convention, and contains a lense, lense mask, rear housing, and circuit board and display assembly. The majority of the material is ABS (acrylonitrile butadiene styrene). The lenses are made of polymethyl methacrylate (PMMA).

#### 4.13.1.3 Mass Reduction Industry Trends

The industry is beginning to use advanced technology for plastic material weight savings. A few pioneers are Trexel, PolyOne, and 3M. Trexel's MuCell process, PolyOne's Chemical Foaming Agents (CFAs), and the 3M Glass Bubble technologies are detailed further in **Section 4.3**.

#### 4.13.1.4 Summary of Mass Reduction Concepts Considered

Comparing the options in the industry, MuCell, PolyOne's CFAs and 3M Glass Bubble were considered in the mass reduction brainstorming process as **Table 4.13-4** shows.

**Table 4.13-4: Summary of Mass Reduction Concepts Initially considered for the Info, Gage and Warning System**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **IP Cluster** | | | |
| Cluster Mask Assy | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Cluster Mask Assy | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Cluster Mask Assy | Use 3M glass bubbles | 6% Mass Reduction | Has to be premixed with plastic resin, Handle with care. |
| Cluster Rear Housing | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Cluster Rear Housing | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Cluster Rear Housing | Use 3M glass bubbles | 6% Mass Reduction | Has to be premixed with plastic resin, Handle with care. |
| Display Housing | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Display Housing | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Display Housing | Use 3M glass bubbles | 8.55% Mass Reduction | Has to be premixed with plastic resin, Handle with care. |
| **Traffic Horn** | | | |
| Outer plastic cover | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Outer plastic cover | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Outer plastic cover | Use 3M glass bubbles | 6% Mass Reduction | Has to be premixed with plastic resin, Handle with care. |
| Outside stl cover | Alumunim | 45% Mass Reduction | High cost, hard to manufacture |
| Outside stl cover | Plastic | 79% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture |
| Outside stl cover | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Outside stl cover | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Outside stl cover | Use 3M glass bubbles | 6% Mass Reduction | Has to be premixed with plastic resin, Handle with care. |
| Outside stl cover | Combo, plastic and MuCell | 81% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture, can't do class "A" surface, Added capital cost |
| Outside stl cover | Combo, plastic and PolyOne | 81% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture, can do class "A" surface, No added capital cost |
| Outside stl cover | Combo, plastic and 3M glass bubbles | 79% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture, Has to be premixed with plastic resin, Handle with care. |
| Mounting brkt | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Mounting brkt | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Mounting brkt | Use 3M glass bubbles | 6% Mass Reduction | Has to be premixed with plastic resin, Handle with care. |
| Mounting brkt | Alumunim | 45% Mass Reduction | High cost, hard to manufacture |
| Mounting brkt | Plastic | 79% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture |
| Mounting brkt | Use MuCell gas process | 10% Mass Reduction | can't do class "A" surface, Added capital cost |
| Mounting brkt | Use Polyone foaming agent | 10% Mass Reduction | can do class "A" surface, No added capital cost |
| Mounting brkt | Use 3M glass bubbles | 6% Mass Reduction | Has to be premixed with plastic resin, Handle with care. |
| Mounting brkt | Combo, plastic and MuCell | 81% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture, can't do class "A" surface, Added capital cost |
| Mounting brkt | Combo, plastic and PolyOne | 81% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture, can do class "A" surface, No added capital cost |
| Mounting brkt | Combo, plastic and 3M glass bubbles | 79% Mass Reduction | close cost to steel when weight is reduced, easy to manufacture, Has to be premixed with plastic resin, Handle with care. |

#### 4.13.1.5 Selection of Mass Reduction Ideas

PolyOne was selected for cost analysis on the cluster mask assembly, the cluster rear housing and the display housing parts in this subsystem. PolyOne was applied to parts that the customer can and cannot see. The component, driver information center screen was not applicable for PolyOne. The ideas were applied to the components shown in **Table 4.13-5**

**Table 4.13-5: Mass Reduction Ideas Selected for the Info, Gage and Warning System**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **13** | **00** | **00** | **Info,Gage and Warning system** | |
| **13** | **01** | **01** | **Drivers Info Center** | |
| | | | Cluster Mask Assy | Use Polyone foaming agent |
| | | | Cluster Rear Housing | Use Polyone foaming agent |
| | | | Display Housing | Use Polyone foaming agent |
| **13** | **01** | **01** | **Traffic Horn Assembly - LH** | |
| | | | Outer plastic cover | Use Polyone foaming agent |
| | | | Outside stl cover | Combo, plastic and PolyOne |
| | | | Mounting brkt | Combo, plastic and PolyOne |
| **13** | **01** | **02** | **Traffic Horn Assembly - RH** | |
| | | | Outer plastic cover | Use Polyone foaming agent |
| | | | Outside stl cover | Combo, plastic and PolyOne |
| | | | Mounting brkt | Combo, plastic and PolyOne |

**Image 4.13-2 (Left): Cluster Mask Assembly**

**Image 4.13-3 (Right): Cluster Rear Housing**

*(Source: FEV, Inc.)*

**Image 4.13-4 (Left): Display Housing**

**Image 4.13-5 (Right): Horn Outer Plastic Cover**

*(Source: FEV, Inc.)*

**Image 4.13-6 (Left): Horn mounting Bracket**

**Image 4.13-7 (Right): Horn Outside Steel Cover**

*(Source: FEV, Inc.)*

### 4.13.2 Info, Gage, and Warning System Mass Reduction / Compounding

This project recorded a system mass reduction of 0.248kg (15.72%) at a cost decrease of $.66 ($2.66per kg). Furthermore, the contribution of the Information, Gage, and Warning

Device System to the overall vehicle mass reduction is 0.01%. There are no compounding mass reductions for this system.

#### 4.13.2.1 Mass Reduction and Cost Impact

**Table 4.13-6** shows a summary of the overall cost impact driven by the weight reduction applied to the Info, Gage and Warning System.

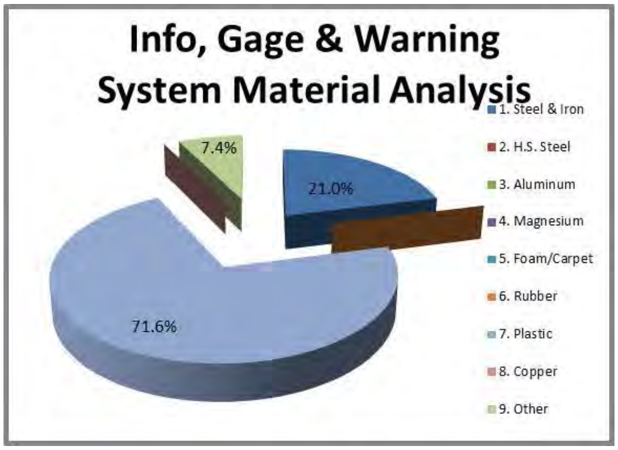
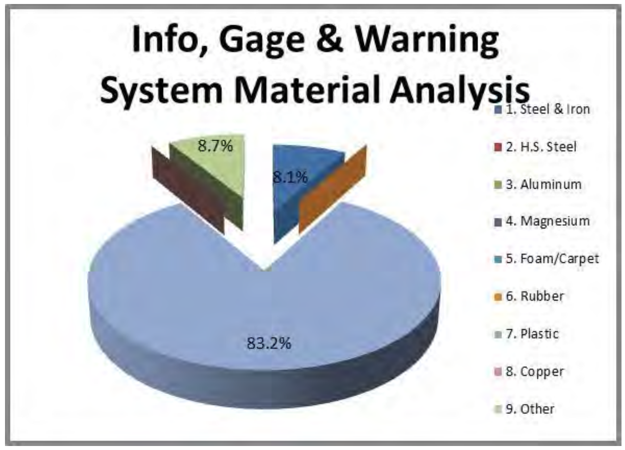
**Table 4.13-6: Calculated Subsystem Mass Reduction and Cost Impact Results for the Info, Gage and Warning System**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction: Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 00 | 00 | Info,Gage and Warning system | | | | | | | | |
| 13 | 01 | 00 | Driver Information Module (Instrument Cluster) | 0.064 | 0.00 | 0.064 | $0.49 | $0.00 | $0.49 | $7.67 | 0.00% |
| 13 | 02 | 00 | Traffic Horns (Electric) | 0.185 | 0.00 | 0.185 | $0.17 | $0.00 | $0.17 | $0.93 | 0.01% |
| | | | | 0.248 (Decrease) | 0.00 | 0.248 (Decrease) | $0.66 (Decrease) | $0.00 | $0.66 (Decrease) | $2.66 (Decrease) | 0.01% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.13.3 Info, Gage, and Warning Device System Material Analysis

A material breakdown for the base Info, Gage, and Warning Device System and for the light weighted and compounded Transmission System is provided in **Figure 4.13-2**. The "Steel & Iron" content category was reduced by nearly 13%, while "Plastic" increased by 11.6%.

| Baseline Info, Gage, and Warning Device System | Total Info, Gage and Warning Device System |
|---|---|
|  |  |





| | | Material Categories: | | | Material Categories: |
|---|---|---|---|---|---|
| 21.0% | 0.332 | 1. Steel & Iron | 8.1% | 0.108 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel | 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum | 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium | 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet | 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber | 0.0% | 0.000 | 6. Rubber |
| 71.6% | 1.130 | 7. Plastic | 83.2% | 1.106 | 7. Plastic |
| 0.0% | 0.000 | 8. Copper | 0.0% | 0.000 | 8. Copper |
| 7.4% | 0.116 | 9. Other | 8.7% | 0.116 | 9. Other |
| 100% | 1.578 | TOTAL | 100% | 1.330 | TOTAL |

**Figure 4.13-2: Calculated Info, Gage, and Warning Device System Baseline Material and Total Material Content**

## 4.14 Electrical Power Supply System

The Electrical Power Supply System is made up of one subsystem, the Service Battery Subsystem. As shown in **Table 4.14-1**.

**Table 4.14-1: Electrical Power Supply System**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 14 | 00 | 00 | Electrical Power Supply System | 21.118 |
| | | | Total System Mass = | 21.118 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 0.86% |

The electrical power supply system is made up of the battery and battery tray assembly as shown in **Image 4.14-1**.

**Image 4.14-1: Chevrolet Silverado battery assembly**
*(Source: A2mac1 database)*

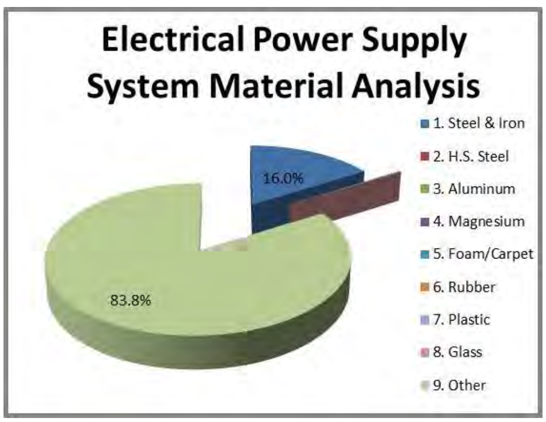
The Electrical Power Supply System, as displayed in **Table 4.14-2**, resulted in 12.8 kg of mass reductions with a cost increase. This reduction resulted from converting the battery from lead acid to lithium-ion and the battery trays from steel to plastic.

**Table 4.14-2: Mass-Reduction and Cost Impact for the Electrical Power Supply System**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys./ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 14 | 00 | 00 | Electrical Power Supply System | | | | | | |
| 14 | 01 | 00 | Service Battery Subsystem | | 12.806 | -$172.73 | -$13.49 | 60.64% | 0.52% |
| | | | | X | 12.806 (Decrease) | -$172.73 (Increase) | -$13.49 (Increase) | 60.64% | 0.52% |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

**Figure 4.14-1: Calculated Material Content for the Electrical Power Supply base BOM**




| | | Material Categories: |
|---|---|---|
| 16.0% | 3.371 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 0.2% | 0.040 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 83.8% | 17.707 | 9. Other |
| 100% | 21.118 | TOTAL |

## 4.14.1 Service Battery Subsystem

### 4.14.1.1 Subsystems Content Overview

A breakdown of the Service Battery Subsystem is shown in **Table 4.14-3**. This subsystem is made up of the Battery Heat Shield & Battery Management System Sub-subsystem and this makes up the 21.118kg of the 21.118 kg system mass. This includes the battery, battery tray, axillary battery support tray as well as the brackets and attachments.

**Table 4.14-3: Service Battery Subsystem Breakdown**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 14 | 00 | 00 | Electrical Power Supply System | |
| 14 | 01 | 00 | Service Battery Subsystem | |
| 14 | 01 | 01 | Battery Heat Shield & Battery Management System | 21.118 |
| | | | | |
| | | | Total Subsystem Mass = | 21.118 |
| | | | Total System Mass = | 21.118 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 100.00% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.86% |

#### 4.14.1.2 Baseline System Technology

Base line technologies for the battery systems have a wide range of technologies in them. While some have a more traditional technology some tend to more in the fore front with their technologies.

The Chevrolet Silverado Battery system is one for the more common in technologies; it has a basic lead acid battery. **Figure 4.14-2** shows the battery system while in is the Silverado's battery.

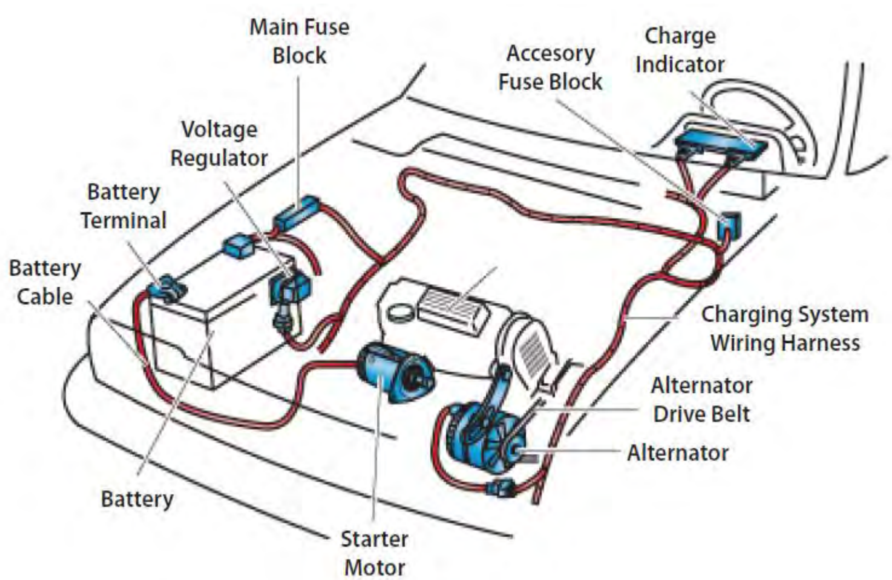



**Figure 4.14-2: 2011 Battery System**
*(Source: http://motorist.org)*


**Image 4.14-2: 2011 Chevrolet Silverado Battery**
*(Source: FEV, Inc.)*

The Chevrolet Silverado Battery system also has a more common steel battery tray and steel brackets for attachment. **Image 4.14-3** shows the Silverado's battery tray.


**Image 4.14-3: 2011 Chevrolet Silverado Battery Tray**
*(Source: FEV, Inc.)*

The Chevrolet Silverado Battery system has an auxiliary battery tray that was not in use. This adds unneeded weight to the vehicle. (**Image 14-1**), shows the Silverado's auxiliary battery tray.

**Image 4.14-4: 2011 Chevrolet Silverado Auxiliary Battery Tray**
*(Source: FEV, Inc.)*

#### 4.14.1.3 Mass-Reduction Industry Trends

There are many different types of automotive batteries currently on the market. Considering the way the automotive industry is progressing with more electric vehicles and more start-stop systems, battery manufactures have been working to come up with the lightest most cost effective battery. Some of the types of battery for automotive applications are:

**Lead-acid battery**. This is the most common battery type and is made up of plates, lead, and lead oxide (various other elements are used to change density, hardness, porosity, etc.) with a 35% sulfuric acid and 65% water solution. This solution is called electrolyte, which causes a chemical reaction that produces electrons.

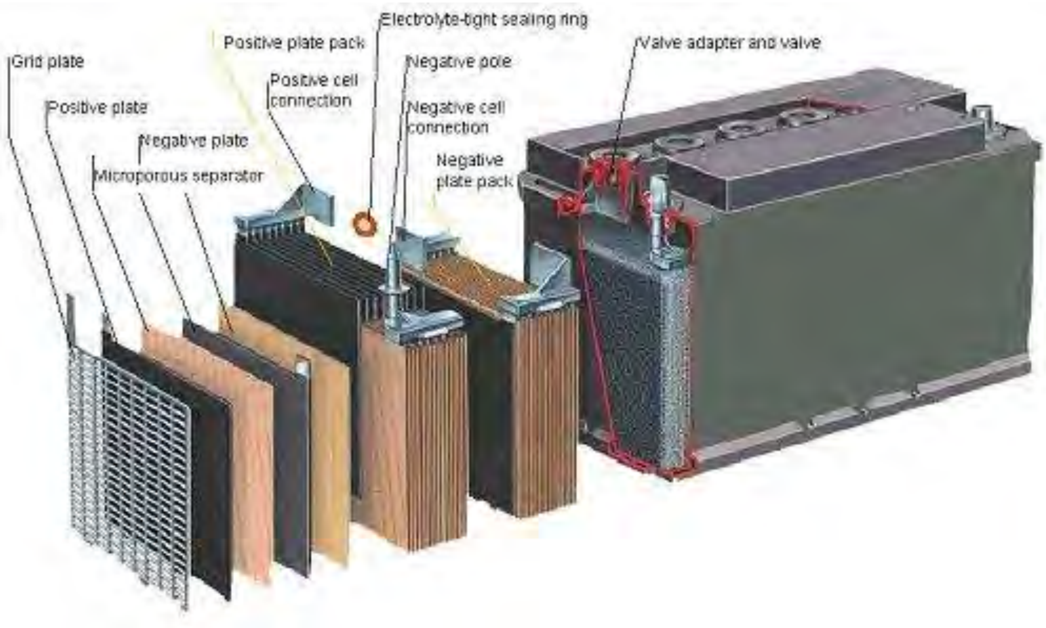



**Figure 4.14-3: 2011 Common Lead Acid Battery Buildup**
*(Source: http://www.batteryfaq.org)*

**Nickel–zinc battery.** Nickel is more costly than the lead used in lead-acid batteries. However, nickel-zinc cells have higher specific energy, energy density, and specific power than do lead-acid cells. NiZn technology is well suited for fast recharge cycling. 90% of the constituent materials are recoverable.

**Lithium–ion polymer battery (Li-Polymer)**. A distinct battery type from Li-Ion batteries: the difference between them lies in the material used as the separator. Rather than an inert substance with holes covered in electrolyte, the separator is made of a micro-porous polymer covered in an electrolytic gel that also serves as a catalyst that reduces the energy barrier in the chemical reaction between cathode and anode. Therefore, Li-Polymer batteries allow for a slight increase in energy density. However, this advantage is offset by a 10% to 30% cost increase. Therefore, because the same materials are used for cathode and anode, Li-Polymer batteries follow the same chemical process as Li-Ion batteries and are not a distinct class.

**Lithium–ion battery (Li-Ion)**. These batteries provide light-weight, high-energy density power sources. Because of their light weight, Li-Ion batteries are used for energy storage for many electric vehicles for everything from electric cars to Pedicels, from hybrid vehicles to advanced electric wheelchairs, from radio-controlled models and model aircraft to the Mars Curiosity rover. They are adaptable in a wide variety of shapes and sizes to efficiently fit the devices they power and lighter than other energy-equivalent secondary batteries. Li-Ion batteries feature high open-circuit voltage in comparison to aqueous batteries (such as lead acid, nickel-metal hydride and nickel-cadmium). This is beneficial because it increases the amount of power that can be transferred at a lower current with no memory effect. Self-discharge rate of approximately 5-10% per month, compared to over 30% per month in common nickel metal hydride batteries, approximately 1.25% per month for low self-discharge NiMH batteries and 10% per month in nickel-cadmium batteries.

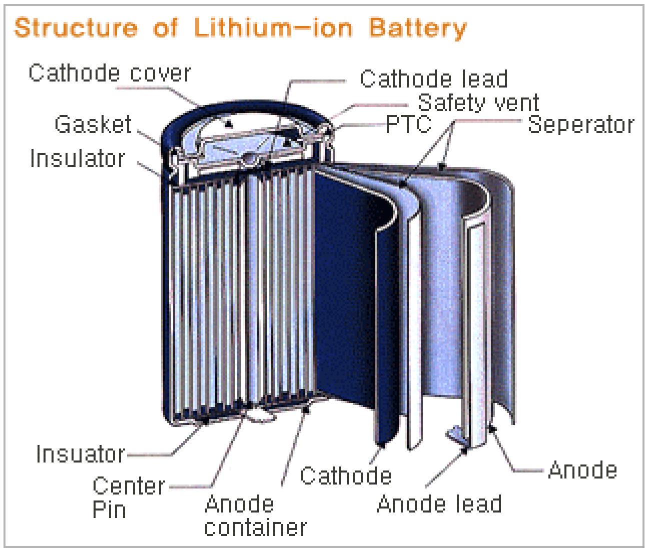



**Figure 4.14-4: 2011 Lithium-Ion Battery Buildup**
*(Source: gm-volt.com)*

Although lithium batteries have a ways to go to be an everyday battery for the automotive market, great strides are being made in the development of the high production lithium-ion battery and by the production years of 2020 - 2025 this will most likely be the battery of choice for car makers.

The lithium-ion battery cost is subject to debate among auto manufacturers and battery manufactures. The Deutsche Bank performed a lithium-ion battery cost forecast for 2020, and the outcome was that the kWh cost would be approximately $250 per kWh. Based on this information, the following figure shows the FEV battery cost calculation.

**<u>Cost</u>**

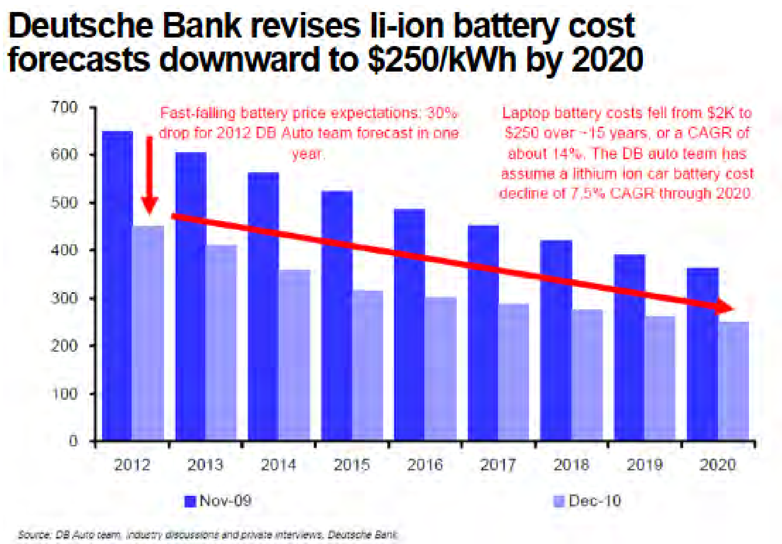



**Figure 4.14-5: Deutsche Bank Battery Cost Forecast, 2010 Study**

*(Source: http://www.alloutcars.com/deutsche-bank-revises-li-ion-battery-cost-forecasts-downward)*

Considering this conclusion that the price for lithium-ion batteries will be $250 per kWh come 2020, then a 70AH 12V battery (or .84 kWh) using $240 per kWh can be predicted to equal $201.60 (FEV's estimate being $201.49). Although this study focused mainly on EV batteries, FEV believes that using the same formula for main battery replacement is not a far stretch. Also assuming a 2025 time frame this cost per kWh will be even lower.

The battery weight is also a debatable point. **Figure 4.14-6** shows an example of the potential weight saves.

## Weight

The Smart Battery SB75 offers state of the art technology "Lithium Iron Phosphate" the safest and most robust lithium chemistry. Capable of reaching over 5000 cycles, The SB75 can be re-charged thousands of times providing 100% DOD (depth of discharge) The Smart Battery SB75 is perfect for boats, trolling motors, cars and almost any application that would use a 12V 75AH lead acid, agm or gel battery.

**FEATURES**

- Fully automatic built in battery protection system
- Automatic low voltage cut off - 8v
- Automatic over voltage cut off - 16v
- Automatic short circuit cut off - instant
- Automatic internal cell balancing
- High quality bolted cylindrical cell design
- Built in cell safety fuse " Nano Cell Fuse Technology "
- Long life 3000 - 5000 cycles
- Lightweight - up to 70% lighter than lead
- No voltage sag - faster cranking for motors and higher voltage for continuous consistent power.
- Dry Battery - no toxic lead or acid
- Zero Maintenance
- No venting or gassing
- Heavy duty stainless steel bolts, washers and flat washers included
- 99.1% efficient
- Green ROHS compliant - No Lead
- Use 100% of rated capacity
- Does not heat up during use
- Connect in series or in parallel
- One battery for 12v, 24v, 36, or 48v applications


**Figure 4.14-6: Potential Weight Savings of a Smart Battery Li-Ion Battery**

The features cited states that up to a 70% weight savings can be achieved with the lithium-ion battery. The original 70AH battery weighed 17.8kg. The lithium-ion's estimated 5.9kg was a 67% savings with regards to FEV's study.

Claus Mochel, marketing director for Atmel Corporation, in a 2011 article wrote: "There is no stopping the relentless march of lithium-ion batteries in e-vehicles (EV) and hybride-vehicles (HEV). In the meantime, nearly every vehicle manufacturer develops a battery of this kind for its fleet and some have already launched series production. The use of Li-ion technology is no longer limited to high-performance batteries for e-vehicles and hybrid vehicles. Li-ion batteries are now also available on the market for 12V automotive on-board power supply systems.

"In the initial phase, the target market was motor racing and technology-minded customers of sports car makers. ***The strongest motivator was a reduction in weight of over 60%, which could be achieved by using Li-ion batteries compared to standard lead-acid batteries.*** As is frequently the case, motor sport merely plays a pioneering role, and several major carmakers are now working on 12V Li-ion on-board power supply batteries for their fleet of production vehicles. This comes as no surprise given the obvious benefits offered by Li-ion technology. In addition to their lower weight, Li-ion batteries reduce the load on the alternator as they retain more power and are able to handle the charge faster than lead-acid batteries. This results in reduced fuel consumption and thus reduced CO2 emissions.

"In addition, Li-ion batteries offer distinct benefits with vehicles featuring start-stop systems. While the life expectancy of lead-acid batteries—which are subject to constant stress from repetitive engine starts—is only approximately 1.5 to 2 years, tests have shown that Li-ion batteries can withstand robust use for over 6 years or more. The longer service life combined with the far higher volume of Li-ion batteries anticipated in the future—due to their increased use in e-vehicles, hybrid vehicles, and vehicles with start-stop function—will inevitably result in considerable reductions in the cost of Li-ion technology, which currently is still admittedly expensive." (©2011 Atmel Corporation)

A November 2009 article at https://www.geek.com/mobile/porsches-weight-saving-lithium-ion-car-battery-1700-1364215/ states that more than a 63% weight savings can be achieved, referencing Porsche's lithium-ion solution: "Weight is the enemy of fuel economy on the highway and quick lap times on the track. Porsche has one solution in the form of a lithium-ion replacement starter (main) battery that weighs in at just 13 pounds vs. 35 pounds for the traditional lead acid battery. "Less weight naturally means greater agility and driving dynamics," Porsche notes in its release. This four-cell battery runs $1,700 which, Porschephiles will be quick to agree, isn't all that much for a Porsche option. It's available on the 2010 Porsche 911 GT3, 911 GT3 RS, and Boxster Spyder. You get the standard lead acid battery as well and the two can be quickly swapped for track days.

"Porsche says the two batteries have the same fastening points, connections, and voltage range. Dimensions are the same except the lithium battery is 2.8″ lower. It has a capacity of 18 amp-hours vs. 60 Ah for a standard lead-acid battery, but the lithium-ion battery delivers all its power, Porsche says, while a standard battery delivers about 30% of what's available. Porsche also says the lithium-ion battery has more charge-discharge cycles and is quicker to recharge. Porsche recommends against using the lithium battery below 32 degrees because of its characteristics. You can charge it and jump-start like a normal battery and the internal electronics protect against overcharge situations."

## Cold Start

The cold start issue is addressed by the battery manufactures. With current progress, it is felt that by the 2020-2025 timeframe all cold start issues will be resolved. A123 Systems has addresses the cold start issue, saying in the following release that their new technology will have 90% original capacity at 113°F and a 20% power increase at temperatures as low as -22°F.

## A123 Systems Introduces Breakthrough Lithium Ion Battery Technology That Optimizes Performance in Extreme Temperatures

WALTHAM, Mass., June 12, 2012 (GLOBE NEWSWIRE) -- A123 Systems (Nasdaq:AONE), a developer and manufacturer of advanced Nanophosphate® lithium iron phosphate batteries and systems, today introduced Nanophosphate EXT™, a new lithium ion battery technology capable of operating at extreme temperatures without requiring thermal management. Nanophosphate EXT is designed to significantly reduce or eliminate the need for heating or cooling systems, which is expected to create sizeable new opportunities within the transportation and telecommunications markets, among others.

"We believe Nanophosphate EXT is a game-changing breakthrough that overcomes one of the key limitations of lead acid, standard lithium ion and other advanced batteries. By delivering high power, energy and cycle life capabilities over a wider temperature range, we believe Nanophosphate EXT can reduce or even eliminate the need for costly thermal management systems, which we expect will dramatically enhance the business case for deploying A123's lithium ion battery solutions for a significant number of applications," said David Vieau, CEO of A123 Systems. "We continue to emphasize innovation with a commercial purpose, and we expect Nanophosphate EXT to strengthen our competitive position in existing target markets as well as create new opportunities for applications that previously were not possible to cost-effectively serve with lithium ion batteries."

Unlike lead acid or other advanced battery technologies, Nanophosphate EXT is designed to maintain long cycle life at extreme high temperatures and deliver high power at extreme low temperatures. According to the testing performed to date at the Ohio State University's Center for Automotive Research (CAR) and the very low observed rate of aging, cells built with A123's Nanophosphate EXT are expected to be capable of retaining more than 90 percent of initial capacity after 2,000 full charge-discharge cycles at 45 degrees Celsius. CAR has also starting testing the cold temperature performance of Nanophosphate EXT, which A123 expects will deliver a 20 percent increase in power at temperatures as low as minus 30 degrees Celsius.

**Figure 4.14-7: A123 Systems Li-Ion Nanophosphate EXT Battery Technology Release**
*(Source: http://www.a123systems.com/media-room-2012-press-releases.htm)*

Some battery manufactures are producing lithium-ion battery for automotive applications. For example, Hitachi, Ltd. and Hitachi Vehicle Energy, Ltd. which develops and manufactures lithium-ion batteries for automotive applications (such as that in **Image 4.14-5**), have a fourth-generation lithium-ion battery that is small, light, and able to provide the world's highest output.


**Image 4.14-5: Hitachi Lithium-Ion Battery**
*(Source: http://www.hitachi.com/New/cnews/090519a.html)*

Plastics are now used extensively in battery tray assemblies, depending on their application and purpose. The 2012 Ford F150 battery tray assembly was utilized as a design that would reduce both assembly and mass on the Silverado. **Image 4.14-6** shows the schematic for the F150 battery tray assembly.

**Image 4.14-6: 2012 Ford F150 Battery Tray Assembly**
*(Source: A2mac1 database)*

A straight comparison was done with the Silverado's battery tray and the Ford F150 battery tray. This was performed without removing any brackets and attachment methods. More weight loss and cost may be removed from the Silverado's battery tray brackets and attachment points with an in-depth study.

**Table 4.14-4: Summary of Mass-Reduction Concepts Initially Considered for the Electrical Power Supply System**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| **Electrical Power Supply System** | | | |
| Battery | Change Service Battery to Lithium-Polymer Chemistry | 53% Mass Reduction | **Risk:** Cost increase, Require priming when first used and have a low self-discharge<br>**Benefit:** Smaller in size |
| Battery | Change to Lithium-Ion Battery | 66% Mass Reduction | **Risk:** Cost increase<br>**Benefit:** higher energy density, less to manufacture than Lithium-Polymer |
| Battery | Change to Nickel-zinc Battery | 45% Mass Reduction | **Risk:** high rate of self-discharge; NiMH batteries lose up to 20% of their charge on the first day<br>**Benefit:** NiZn batteries provide sustained, high charge acceptance over a much longer life span, 90% of the constituent materials recoverable. |
| Battery | Change to EESTOR battery | 90% Mass Reduction | **Risk:** EEStor's technology has been regarded, in some quarters, as controversial.<br>**Benefit:** Lighter weight |
| Battery tray | Change from steel to PP-GF30 Plastic | 34% weight save & cost increase | **Risk:** Cost increase<br>**Benefit:** Lighter weight, non-rusting, used F150 as exsample |
| Battery tray | Change from steel to aluminum | 25% weight save & cost increase | **Risk:** Cost increase<br>**Benefit:** Lighter weight, non-rusting |
| Aux Battery tray | Change from steel to PP-GF30 Plastic | 34% weight save & cost increase | **Risk:** Cost increase<br>**Benefit:** Lighter weight, non-rusting |
| Aux Battery tray | Change from steel to aluminum | 25% weight save & cost increase | **Risk:** Cost increase<br>**Benefit:** Lighter weight, non-rusting |

### 4.14.1.4 Selection of Mass Reduction Ideas

The mass reduction ideas that were selected for the Electrical Power Supply System are listed in **Table 4.14-5**.

**Table 4.14-5: Mass-Reduction Ideas Selected for Detail Analysis of the Electrical Power Supply System**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **14** | **00** | **00** | **Electrical Power Supply System** | |
| **14** | **01** | **01** | **Battery Heat Shield & Battery Management System** | |
| | | | Battery | Change to Lithium-Ion Battery |
| | | | Battery Tray | Used PP-GF30, Used F150 as ref. |
| | | | Aux Battery Tray | Used PP-GF30 |

## 4.14.2 Secondary Mass Reduction / Compounding

### 4.14.2.1 Mass-Reduction & Cost Impact Results

The mass reductions that resulted for the Electrical Power Supply System are shown in **Table 4.14-6**. This project recorded a system mass reduction of 12.81 kg (60.6%) at a cost increase of $172.73, or $13.49/ kg. The contribution of the Electrical Power Supply System to the overall vehicle mass reduction is 0.54%. There are no compounding mass reductions for this system.

**Table 4.14-6: Mass-Reduction and Cost Impact for the Electrical Power Supply System**

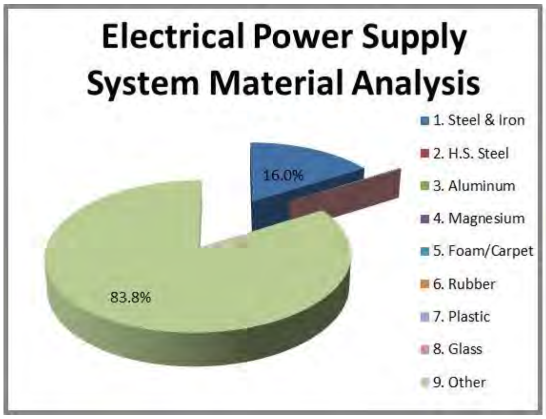
| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 14 | 00 | 00 | Electrical Power Supply System | | | | | | | | |
| 14 | 01 | 00 | Service Battery Subsystem | 12.81 | 0.00 | 12.81 | -$172.73 | $0.00 | -$172.73 | -$13.49 | 0.52% |
| | | | | 12.81 (Decrease) | 0.00 | 12.81 (Decrease) | -$172.73 (Increase) | $0.00 | -$172.73 (Increase) | -$13.49 (Increase) | 0.52% |

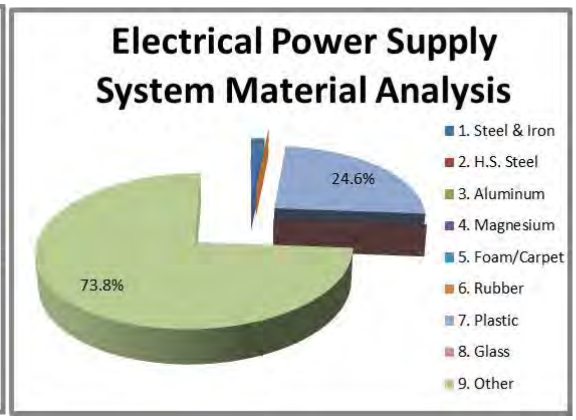
(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.14.3 Electrical Power Supply System Material Analysis

A material breakdown for the base Transmission System and for the light weighted and compounded Transmission System is provided in **Figure 4.14-8**. The “Steel & Iron” content category was reduced by 14.4%, while “Plastic” increased by 24.4%.

**Base Material Content** | **Total Material Content**




| Base % | Base Mass | Material Categories: | Total % | Total Mass | Material Categories: |
|---|---|---|---|---|---|
| 16.0% | 3.371 | 1. Steel & Iron | 1.6% | 0.130 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel | 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum | 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium | 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet | 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber | 0.0% | 0.000 | 6. Rubber |
| 0.2% | 0.040 | 7. Plastic | 24.6% | 1.965 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass | 0.0% | 0.000 | 8. Glass |
| 83.8% | 17.707 | 9. Other | 73.8% | 5.902 | 9. Other |
| 100% | 21.118 | TOTAL | 100% | 7.998 | TOTAL |

**Figure 4.14-8: Calculated Material Content between Baseline Material and Total Material Content**

## 4.15 In-Vehicle Entertainment System

Chevrolet Silverado has a baseline entertainment system, with a basic radio, CD, MP3, and USB input connection. The mass is shown in **Table 4.15-1**.

**Table 4.15-1: Baseline Subsystem Breakdown for In-Vehicle Entertainment System**

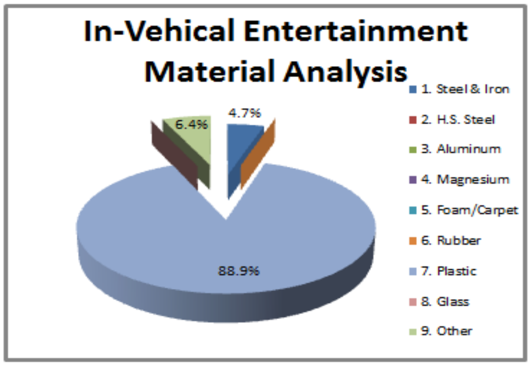
| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 15 | 00 | 00 | In-Vehicle Entertainment System | |
| 15 | 01 | 00 | Receiver and Audio Media Subsystem | 1.731 |
| 15 | 02 | 00 | Antenna Subsystem | 0.502 |
| | | | | |
| | | | Total System Mass = | 2.233 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 0.09% |

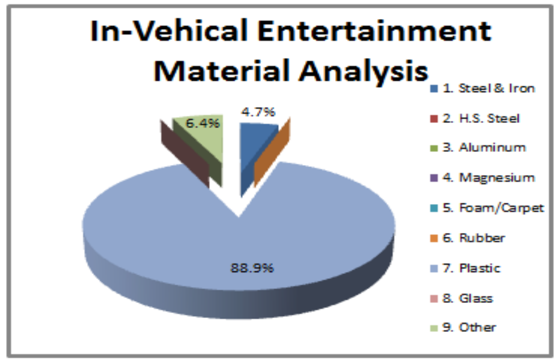
**Image 4.15-1: Delphi Ultra-Light Radio Designs**
*(Source: Delphi.com)*

The Silverado in this study has a Delphi ultra-light plastic case radio design with insert-molded electromagnetic compatibility (EMC) shielding. This design is available on Chevrolet and GMC full size pick-ups and sport utility vehicles. It won top recognition at the 2009 39th Annual Society of Plastics Engineers International (SPE) Automotive Innovation Awards ceremony, Livonia, Michigan. This radio is half the mass of steel case systems otherwise used in the infotainment industry.

Portable entertainment systems are quickly becoming a necessity for families of all sizes. New fleets of cars and minivans are equipped standard with the latest DVD player and overhead TV screens. Luxury cars are no longer the only vehicles installed with premium entertainment accessories such as iPod jacks, Wi-Fi, surround sound MP3 players, and cinematic options with video players: Pickup trucks and SUVs have the same infotainment options as other vehicles.

**Baseline In-Vehicle Entertainment System** **Total In-Vehicle Entertainment System**




| | | Material Categories: |
|---|---|---|
| 4.7% | 0.129 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 88.9% | 2.431 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 6.4% | 0.175 | 9. Other |
| 100% | 2.735 | TOTAL |

| | | Material Categories: |
|---|---|---|
| 4.7% | 0.129 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 88.9% | 2.431 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 6.4% | 0.175 | 9. Other |
| 100% | 2.735 | TOTAL |

**Figure 4.15-1: Calculated In-Vehicle Entertainment System Baseline Material and Total Material Content**

### 4.15.1 In-Vehicle Receiver and Audio Media Subsystem

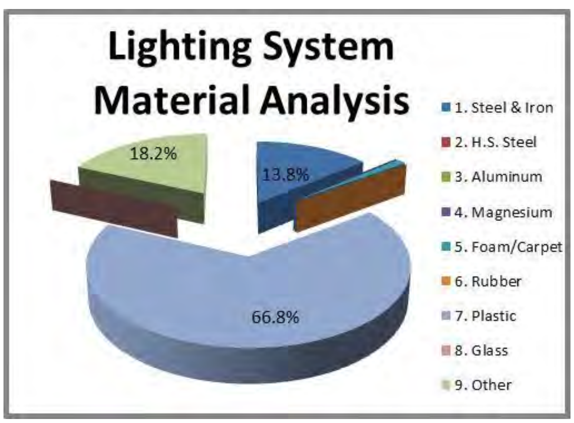
FEV did not see any opportunities to reduce the current overall mass on this system. It is to note that the Delphi in-vehicle entertainment system is the same FEV cited as a weight-saving example in the EPA study, *"Light-Duty Vehicle Mass Reduction and Cost Analysis – Midsize CUV (EPA-420-R12-026)."*

## 4.16 Lighting System

The Lighting System (broken down in **Table 4.16-1**) consisted of the Front Lighting, Interior Lighting, Rear Lighting, Special Mechanisms, and the Light Switches Subsystems. There is no mass for either the Interior Lighting or the Special Mechanisms Subsystems as these components were kept with their respective interior assemblies (e.g., headliner or instrument panel).

**Table 4.16-1: Baseline Subsystem Breakdown for the Lighting System**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| 17 | 00 | 00 | Lighting System | |
| 17 | 01 | 00 | Front Lighting Subsystem | 6.699 |
| 17 | 02 | 00 | Interior Lighting Subsystem | 0.000 |
| 17 | 03 | 00 | Rear Lighting Subsystem | 2.736 |
| 17 | 04 | 00 | Lighting - Special Mechanisms Subsystem | 0.000 |
| 17 | 05 | 00 | Light Switches Subsystem | 0.125 |
| | | | Total System Mass = | 9.560 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 0.39% |




| | | Material Categories: |
|---|---|---|
| 13.8% | 1.324 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 1.2% | 0.113 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 66.8% | 6.387 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 18.2% | 1.737 | 9. Other |
| 100% | 9.560 | TOTAL |

**Figure 4.16-1: Calculated Material Content for the Base BOM**

The Front Lighting Subsystem, as seen in **Table 4.16-2**, resulted in 0.386 kg of mass reductions with a cost increase of -$2.00 The Rear Lighting Subsystem did not result in mass reduction ideas. A foaming agent could not be applied to the rear tail lamp housings because the reflective coating's aesthetic quality would be reduced. The front headlamp housings have separate reflectors and thus require no coating to be applied.

**Table 4.16-2: Mass Reduction and Cost Impact for the Lighting System**

| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction Idea: Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Subsys./ Subsys. Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 17 | 00 | 00 | **Lighting System** | | | | | | |
| 17 | 01 | 00 | Front Lighting Subsystem | | 0.386 | -$2.00 | -$5.18 | 5.76% | 0.02% |
| 17 | 02 | 00 | Interior Lighting Subsystem | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 17 | 03 | 00 | Rear Lighting Subsystem | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 17 | 04 | 00 | Lighting - Special Mechanisms Subsystem | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| 17 | 05 | 00 | Light Switches Subsystem | | 0.000 | $0.00 | $0.00 | 0.00% | 0.00% |
| | | | | x | **0.386** (Decrease) | **-$2.00** (increase) | **-$5.18** (increase) | **4.04%** | **0.02%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

## 4.16.1 Front Lighting Subsystem

### 4.16.1.1 Subsystems Content Overview

A breakdown of the Front Lighting Subsystem is shown in **Table 4.16-3**. This subsystem makes up the majority of the Lighting System's mass. This includes the Headlamp Cluster Assembly Sub-subsystem (front headlamps), as well as the Supplemental Front Lamps Sub-subsystem (fog lights).

**Table 4.16-3: Front Lighting Subsystem Breakdown**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| 17 | 01 | 00 | Front Lighting Subsystem | |
| 17 | 01 | 01 | Headlamp Cluster Assembly | 6.179 |
| 17 | 01 | 04 | Supplemental Front Lamps | 0.520 |
| | | | Total Subsystem Mass = | 6.699 |
| | | | Total System Mass = | 9.560 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 70.08% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 0.27% |

#### 4.16.1.2 Baseline System Technology

The Chevrolet Silverado headlamps include incandescent lights, projector lights, and the turn signal indicators. A Silverado front headlamp assembly (**Image 4.16-1**) includes a polypropylene housing (**Image 4.16-2**), a polycarbonate lens, and reflectors made of a bulk molding compound (BMC) (**Image 4.16-3**).

**Image 4.16-1: Chevrolet Silverado Front Headlamp Assembly**

**Image 4.16-2: Chevrolet Silverado Front Headlamp Housing**

*(Source: FEV, Inc.)*

**Image 4.16-3: Chevrolet Silverado Headlamp Assembly Inner Reflector**
*(Source: FEV, Inc.)*

### 4.16.1.3 Mass Reduction Industry Trends

High Intensity Discharge (HID) and LED lights are becoming popular choices both for visibility and for styling. These lights may offer mass reduction but usually weigh and cost more than their traditional counterparts.

HID lights have ballast which adds mass and cost to the headlamp. LED produce heat at the light source and may require heat sinks or cooling fans. These cooling solutions add mass and cost to the headlamp.

Various types of plastics are used in headlamp assemblies depending on their application and purpose. The reflector component helps illuminate the light output of the bulbs and is a relatively dense plastic because of the high heat requirements it needs to maintain. Often times, a Bulk Molding Compound (BMC) is used for the reflectors, which is capable of enduring the elevated temperatures. BMCs have a relatively high density compared to other plastics. SABIC has a product line called Ultem® for this specific application, which is a type of polyetherimide (PEI). These plastics are specifically developed and used for headlamp reflectors so they possess the necessary thermal requirements plus have a lower density compared to BMCs. Typical BMCs have a density of 2 g/cm$^3$ and Ultem PEI has a density of approximately 1.3 g/cm$^3$. In addition, Ultem PEI can be molded in thinner wall sections. SABIC's Ultem material has been used in production and a few examples are shown in **Image 4.16-4.**


**Image 4.16-4: SABIC Ultem Production Application Examples**
*(Photo Courtesy of SABIC)*

Although more expensive from a material standpoint, Ultem saves some cost on processing. When using a PEI such as Ultem, the part can go directly from its injection molding step to metalizing, saving on surface preparation costs. The metalizing often takes place through a process called Physical Vapor Deposition (PVD) for headlamp reflectors.

### 4.16.1.4 Summary of Mass Reduction Concepts Considered

The mass reduction ideas considered for the Front Lighting Subsystem are compiled in **Table 4.16-4**. Trexel's MuCell process is considered for use on applicable plastic housings along with PolyOne's Chemical Foaming Agents, reference **Section 4.3** for more information on these technologies. In addition, the Ultem® PEI material was considered as discussed in the previous section. For the rear tail lamp reflectors, PEI was not applicable as those components were already made of a lightweight PBT plastic.

**Table 4.16-4: Summary of Mass Reduction Concepts Initially Considered for the Front Lighting Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| Front Headlamp Housings | MuCell® | 10% Mass Reduction | Mass reduction with cost savings. Used by Ford in High Volume Programs |
| Base - Front Fog Lamps | PolyOne CFA | 10% Mass Reduction | Cannot use for Fog Lamp Base |
| Front Headlamp Inner Reflectors | Replace UP-(MD60+GF20) with SABIC ULTEM | 40-50% Mass Reduction | High Cost - Used on the Audi A1, Cadllac CTS and others |
| Front Fog Lamp Housings | Replace PBT with SABIC ULTEM | 40-50% Mass Reduction | Cannot apply to Front Fog Lamp Housings |
| Front Headlamps | Use LED lighting system | 40-50% Mass Reduction | Design Feature. High Cost, Little mass savings due to heat sinks and cooling systems that are required. |
| Front Fog Lamps | Use LED lighting system | 40-50% Mass Reduction | Design Feature. High Cost, Little mass savings due to heat sinks and cooling systems that are required. |

### 4.16.1.5 Selection of Mass Reduction Ideas

The mass reduction ideas that were selected for the Front Lighting Subsystem are listed in **Table 4.16-5**. MuCell was applied to the Front Headlamp Housings. LEDs were not selected to replace the current bulbs do to the additional required cooling parts.

**Table 4.16-5: Mass Reduction Ideas Selected for Detail Analysis of the Front Lighting Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| **17** | **01** | **00** | **Front Lighting** | |
| 17 | 01 | 01 | Headlamp Housings | MuCell® applied to Housings |
| 17 | 01 | 01 | Headlamp Housings | Front Headlamp Inner Reflectors Replace UP-(MD60+GF20) with SABIC ULTEM |
| | | | | |

### 4.16.2 Secondary Mass Reduction / Compounding

This project recorded a system mass reduction of 0.39 kg (4%) with a cost increase of \$2.00, or \$5.18 per kg. The contribution of the Lighting System to the overall vehicle mass reduction was 0.02%. There are no compounding mass reductions for this system.

#### 4.16.2.1 Mass Reduction and Cost Impact Results

The Front Lighting Subsystem, as seen in **Table 4.16-6**, resulted in 0.386 kg of mass reductions with a cost increase of -\$2.00 The Rear Lighting Subsystem did not result in mass reduction ideas. A foaming agent could not be applied to the Rear Tail Lamp Housings because it would reduce the aesthetic quality of the reflective coating. The Front Headlamp Housings have separate reflectors and thus require no coating to be applied.

**Table 4.16-6: Mass Reduction and Cost Impact for the Front Lighting Subsystem.**

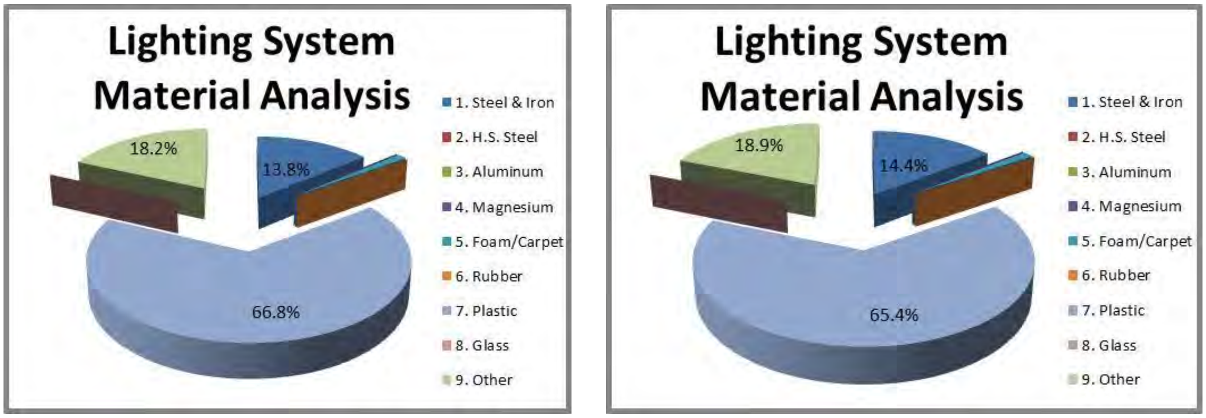
| | | | | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "\$" (2) | Cost Impact Comp "\$" (2) | Cost Impact Total "\$" (2) | Cost/ Kilogram Total "\$/kg" | Vehicle Mass Reduction Total "%" |
| | | | 2454 | | | | | | | | |
| **17** | **00** | **00** | **Lighting System** | | | | | | | | |
| 17 | 01 | 00 | Front Lighting Subsystem | 0.386 | 0.00 | 0.386 | -\$2.00 | \$0.00 | -\$2.00 | -\$5.18 | 0.02% |
| 17 | 02 | 00 | Interior Lighting Subsystem | 0.000 | 0.00 | 0.00 | \$0.00 | \$0.00 | \$0.00 | \$0.00 | 0.00% |
| 17 | 03 | 00 | Rear Lighting Subsystem | 0.000 | 0.00 | 0.00 | \$0.00 | \$0.00 | \$0.00 | \$0.00 | 0.00% |
| 17 | 04 | 00 | Lighting - Special Mechanisms Subsystem | 0.000 | 0.00 | 0.00 | \$0.00 | \$0.00 | \$0.00 | \$0.00 | 0.00% |
| 17 | 05 | 00 | Light Switches Subsystem | 0.000 | 0.00 | 0.00 | \$0.00 | \$0.00 | \$0.00 | \$0.00 | 0.00% |
| | | | | **0.386** (Decrease) | **0.00** | **0.386** (Decrease) | **-\$2.00** (Increase) | **\$0.00** | **-\$2.00** (Increase) | **-\$5.18** (Increase) | **0.02%** |

(1) "+" = mass decrease, "-" = mass increase
(2) "+" = cost decrease, "-" = cost increase

### 4.16.3 Lighting System Material Analysis

A material breakdown for the base Lighting System and for the light weighted and compounded Transmission System is provided in **Figure 4.16-2**. The “Plastic” content category was reduced by 1.4%, while “Steel & Iron” and “Other” increased by 0.6% and 0.7%, respectively.

**Baseline Lighting System** | **Total Lighting System**




| | | Material Categories: |
|---|---|---|
| 13.8% | 1.324 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 1.2% | 0.113 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 66.8% | 6.387 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 18.2% | 1.737 | 9. Other |
| 100% | 9.560 | TOTAL |

| | | Material Categories: |
|---|---|---|
| 14.4% | 1.324 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 1.2% | 0.113 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 65.4% | 6.001 | 7. Plastic |
| 0.0% | 0.000 | 8. Glass |
| 18.9% | 1.737 | 9. Other |
| 100% | 9.174 | TOTAL |

**Figure 4.16-2: Calculated Lighting System Baseline Material and Total Material Content**

## 4.17 Electrical Distribution and Electronic Control System

Cable harnesses are usually designed according to geometric and electrical requirements. The wires are first cut to the desired length, usually using a special wire-cutting machine. The wires may also be printed on by a special machine during the cutting process or later on a separate machine. After this, the coated ends are stripped to expose the metal wires, which are fitted with any required terminals and/or connector housings.

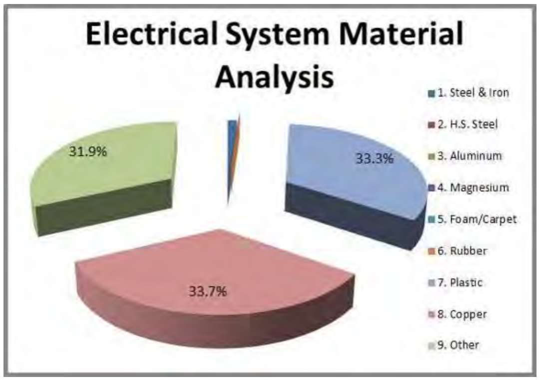
The cables are assembled and clamped together on a special workbench or to a formboard (according to design specification), such as shown in **Image 4.17-1**, to make the cable harness. After fitting any protective sleeves and/or conduit, the harness is either fitted directly into the vehicle or shipped for fitting at a later time and location. Despite increasing automation, cable harnesses continue to be manufactured generally by hand. This will likely remain the case for the immediate future: due to the many different processes involved, cable assembly is difficult to automate. However, these processes can be learned relatively quickly, even without professional qualifications.

**Image 4.17-1: Production Process of Automotive Wire to Formboard**
*(Source: http://www.cfibermfg.com/WiringHarnessGuide.pdf Photo)*

The Electrical Distribution and Electronic Control System is made up of the Electrical Wiring and Circuit Protection Subsystem. As shown in **Table 4.17-1**, this makes up the total system.

**Table 4.17-1: Mass Breakdown by Subsystem for Electrical System.**

| System | Subsystem | Sub-Subsystem | Description | System & Subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 18 | 00 | 00 | Electrical Distribution and Electronic Control System | |
| 18 | 01 | 00 | Electrical Wiring and Circuit Protection Subsystem | 33.595 |
| | | | | |
| | | | Total System Mass = | 33.595 |
| | | | Total Vehicle Mass = | 2454 |
| | | | System Mass Contribution Relative to Vehicle = | 1.37% |




| | | Material Categories: |
|---|---|---|
| 1.2% | 0.399 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 33.3% | 11.184 | 7. Plastic |
| 33.7% | 11.310 | 8. Copper |
| 31.9% | 10.701 | 9. Other |
| 100% | 33.595 | TOTAL |

**Figure 4.17-1: Calculated Base Material Content for the Base BOM**

**Table 4.17-2: Mass Breakdown by Subsystem for Electrical System**

| | | | | Net Value of Mass Reduction Idea | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Subsystem | Sub-Subsystem | Description | Idea Level Select | Mass Reduction "kg" (1) | Cost Impact "$" (2) | Average Cost/ Kilogram $/kg | Sub-Subs./ Sub-Subs. Mass Reduction "%" | Vehicle Mass Reduction "%" |
| 18 | 01 | 00 | Electrical Wiring and Circuit Protection Subsystem | | | | | | |
| 18 | 01 | 01 | Front End and Engine Compartment Wiring | A | 1.497 | $15.34 | $10.25 | 25.86% | 0.06% |
| 18 | 01 | 02 | Instrument Panel Harness | A | 1.704 | $15.91 | $9.34 | 24.76% | 0.07% |
| 18 | 01 | 03 | Body and Rear End Wiring | A | 0.954 | $9.37 | $9.82 | 27.10% | 0.04% |
| 18 | 01 | 04 | Trailer Tow Wiring | A | 1.417 | $13.91 | $9.82 | 27.11% | 0.06% |
| 18 | 01 | 05 | Battery Cables | A | 0.503 | $6.94 | $13.79 | 28.26% | 0.02% |
| 18 | 01 | 06 | Load Compartment Fuse Box / Passive | B | 0.274 | -$0.80 | -$2.92 | 9.30% | 0.01% |
| 18 | 01 | 07 | Interior & Console wiring | A | 0.667 | $0.77 | $1.15 | 47.76% | 0.03% |
| 18 | 01 | 08 | Frt & Rear door harness | A | 1.451 | $0.00 | $0.00 | 80.00% | 0.06% |
| | | | | A | 8.468 (Decrease) | $61.44 (Decrease) | $7.26 (Decrease) | 25.21% | 0.35% |

(1) "+" = mass decrease, "-" = mass increase

(2) "+" = cost decrease, "-" = cost increase

## 4.17.1 Electrical Wiring and Circuit Protection Subsystem

### 4.17.1.1 Subsystem Content Overview

**Table 4.17-3** shows the structure of the Electrical Wiring and Circuit Protection Subsystem. The included sub-subsystems are front end and engine compartment wiring, instrument panel harness, body and rear end wiring, trailer and tow harness, battery cables, load compartment fuse box/passive, interior and console wiring, and headliner and door harnesses. **Image 4.17-2** shows an instrument panel wiring harness.

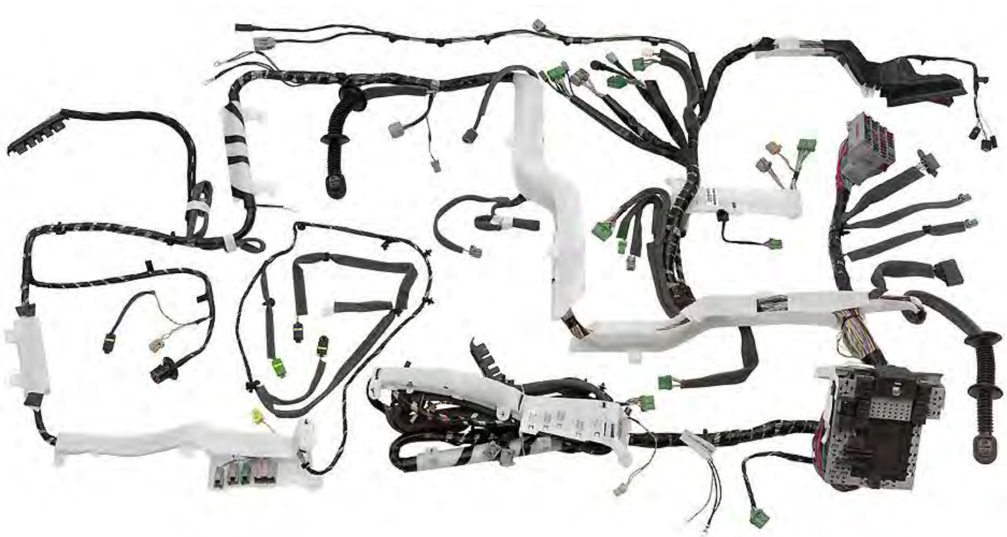


**Image 4.17-2: Instrument Panel Wiring Harness**
*(Source: RB Racing, http://www.rbracing-rsr.com/wiring_ecu.html*

The most significant contributor to the mass of the Electrical Wiring and Circuit Protection Subsystem is the Instrument Panel Harness Sub-subsystem at 6.88 kg. **Table 4.17-3** shows the mass contribution of all included sub-subsystems.

**Table 4.17-3: Mass Breakdown by Sub-subsystem for the Electrical Wiring and Circuit Protection Subsystem**

| System | Subsystem | Sub-Subsystem | Description | Subsystem & Sub-subsystem Mass "kg" |
|---|---|---|---|---|
| | | | | |
| 18 | 01 | 00 | Electrical Wiring and Circuit Protection Subsystem | |
| 18 | 01 | 01 | Front End and Engine Compartment Wiring | 5.791 |
| 18 | 01 | 02 | Instrument Panel Harness | 6.883 |
| 18 | 01 | 03 | Body and Rear End Wiring | 3.519 |
| 18 | 01 | 04 | Trailer Tow Wiring | 5.228 |
| 18 | 01 | 05 | Battery Cables | 1.782 |
| 18 | 01 | 06 | Load Compartment Fuse Box / Passive | 2.945 |
| 18 | 01 | 07 | Interior & Console wiring | 1.397 |
| 18 | 01 | 08 | Frt & Rear door harness | 1.814 |
| 18 | 01 | 99 | Misc. | 4.237 |
| | | | | |
| | | | Total Subsystem Mass = | 33.595 |
| | | | Total System Mass = | 33.595 |
| | | | Total Vehicle Mass = | 2454 |
| | | | Subsystem Mass Contribution Relative to System = | 100.00% |
| | | | Subsystem Mass Contribution Relative to Vehicle = | 1.37% |

#### 4.17.1.2 Chevrolet Silverado Baseline Subsystem Technology

The Chevrolet Silverado's electrical systems follow an industry norm with copper wire contained in PVC insulation. Wire gauge sizes are optimized for current capacities.

#### 4.17.1.3 Mass Reduction Industry Trends

Industry trends for automotive wiring systems allow for a variety for wire and wire sheathing options. The wire compositions come in many combinations, annealed bare copper, silver tin and nickel plated copper, copper clad steel, copper clad aluminum, copper clad magnesium, stranded, single core and flat cables. Reviewing today's market options, each wire type is found to have its different pros and cons. For this study, cost and weight were the most closely examined in order to determine the final selection for mass weight reduction.

#### 4.17.1.4 Summary of Mass Reduction Concepts Considered

The many aspects and variety of new concepts for automotive wiring can be debated for hours to determine the best way forward. For this study, all the previously mentioned concepts were reviewed and given consideration with three key areas in mind: weight, cost and recycling capability. Companies such as Delphi, Sumitomo, Furukawa and Axon Cable produce large amounts of automotive wiring and are moving toward providing new products such as copper-clad aluminum and aluminum wire. Each wiring has respective advantages and disadvantages relating to usage and manufacturing processes, with weight a hot-button issue. As this directly relates to increasing mileage, more OEMs and suppliers are thinking outside the box. Sumitomo developed the aluminum wire harness that was used in the 2010 Toyota Ractis and in the 2011 Toyota Yaris.

Some of the ideas evaluated, but not considered, included: flexible printed circuit, replacing wiring troughs where applicable with BIW, replacing copper conductors with copper-coated aluminum (CCA) conductors, replacing stamped module housings with conductive plastics and/or plating for EMI, eliminating or reducing empty connector cavities, replacing low current and signal wires with copper magnesium (CuMg) alloy conductors, replacing signal leads with brass FLRMSY conductors, and using a fiber optic network or carbon nanotubes. The summary of mass reduction technologies considered is detailed in **Table 4.17-4**.

**Table 4.17-4: Summary of Mass Reduction concepts initially considered for the Electrical Wiring and Circuit Protection Subsystem**

| Component/Assembly | Mass-Reduction Idea | Estimated Impact | Risks & Trade-offs and/or Benefits |
|---|---|---|---|
| All Harness's | Remove PVC coating and replace with PPO coating on orig. copper wire harness's | 20% Mass Reduction | Lower material cost, Lower mass, Smaller wire dia. |
| All Harness's | Aluminum Wire with PPO coating | 43% Mass Reduction | Lower material cost, Added processing needed for connection issue, Larger harness bundle size, |
| All Harness's | Copper Clad Aluminum-CCA wire with PPO coating | 39% Mass Reduction | Higher strength than aluminium, Higher electrical conductivity than pure aluminium, Lighter than pure copper, Lower material cost, Added processing needed for connection issue, Larger harness bundle size, |
| All Harness's | Copper Clad Mag wire with PPO coating | Mass Reduction | High material cost, Added processing needed for connection issue |
| All Harness's | Copper Clad steel wire with PPO coating | Mass Reduction | High material cost, Added processing needed for connection issue |
| IP Harness 1 connector box brkt | From steel to ABS plastic, PolyOne foaming agent for added 10% mass reduction | 33% Mass Reduction | Less tooling, lower material usage, faster cycle time, smaller press size |
| Fuse Box support | Use Polyone foaming agent | 10% Mass Reduction | Less tooling, lower material usage, faster cycle time, smaller press size |
| | Add 3M glass bubbles plastic additive | 18.5% Mass Reduction | Less tooling, lower material usage, Higher mat'l cost |
| Fuse Box - Cover | Use Polyone foaming agent | 10% Mass Reduction | Less tooling, lower material usage, faster cycle time, smaller press size |
| | Add 3M glass bubbles plastic additive | 18.5% Mass Reduction | Less tooling, lower material usage, Higher mat'l cost |
| Headliner wiring | Use flat wire | 80% Mass Reduction | Higher mat'l cost, Trimination issues, Less assy time |
| Frt & Rear door wiring | Use flat wire | 80% Mass Reduction | Higher mat'l cost, Trimination issues, Less assy time |

### 4.17.1.5 Selection of Mass Reduction Ideas

Following the review of today's market innovations and trends, FEV has opted to use aluminum wire and PPO sheathing on all wire harnesses. With these two methods a significant weight and cost savings can be achieved. Flat cable was also used for the headliner and doors. The cost and weight reductions were provided by Axon cable®. The paragraphs below will be broken into sections to discuss the different types of wire, connectors and other items.

#### 4.17.1.5.1 Aluminum Wire

There continue to be some issues with using aluminum wiring, of which aluminum oxidation, coefficient of expansion, creep, and lack of North American aluminum wire production are the most common.

**Image 4.17-3: Aluminum Stranded wire**
*(Source: Google Images)*

The use of newer aluminum alloys, such as Furukawa Automotive Systems 1000 system aluminum wire, as compared to the older 8000 series aluminum wire from the 1970s has created better conductivity, joining, strength and bending by changing some of the alloy properties, such as by adding iron, copper, and magnesium.

Since the newly developed aluminum wire has strength of 200 MPa that is twice as strong as existing aluminum wire, it can be used as a harness around an engine subject to big vibrations and doors subject to impacts created by opening and closing in place of cooper wire. If aluminum wire harness replaces copper wire harness completely in a vehicle, the weight of the total wire harness of a vehicle will be halved. Lighter wire harness contributes to fuel consumption greatly because it is said that reducing the weight of a car by just under 100 kg and improves fuel consumption by 1 km/liter.

Furukawa Electric plans to start shipping samples in 2014 in time for the design of the models to be launched in 2017. The world wire harness market is expected to increase 30% by 2030 over the 2010 levels. Though aluminum wire harness is currently estimated to account for less than 50% of the market, the newly developed aluminum wire will accelerate the replacement from copper wire harness to aluminum wire harness.

The Sumitomo Group is another company that has developed low-voltage aluminum-wired harnesses for automotive use. Stuart Burns, in his article *Aluminum Replacing Copper in Automotive Applications* said: "The Sumitomo Group says it developed the lightweight wiring harnesses using thin aluminum wires with twisted wire structures to ensure reliability of electrical connection. It seems probable we should factor in automotive wiring to become a major driver of aluminum consumption in the years ahead."[46]

While Osaka-based Sumitomo Electric has offered aluminum wiring in the past, such as in the 2010 Toyota Ractis and 2011 Yaris, the products could only be used in limited areas of the vehicle because they were not resistant enough to heat and vibration. The new products could be used throughout a vehicle.

**Image 4.17-4: Sumitomo Electric's Aluminum Electrical Wiring for Toyota Ractis**
*(Source: Sumitomo Electric Industries)*

4.17.1.5.2 Aluminum Wire Connectors

**Image 4.17-5: Delphi Aluminum Capable Terminals**
*(Source: Delphi.com)*

46 *Source: http://agmetalminer.com/2011/03/28/aluminum-replacing-copper-in-automotive-applications/*

Connectors come in different configurations, depending on the manufacturer and the application in the wiring harness. A simple connector idea was put forward by the Sumitomo group was to redesign the conventional connector style. This connector (**Image 4.17-6**) was introduced in a 2011 paper titled *"Development of Aluminum Wiring Harness."*[47]

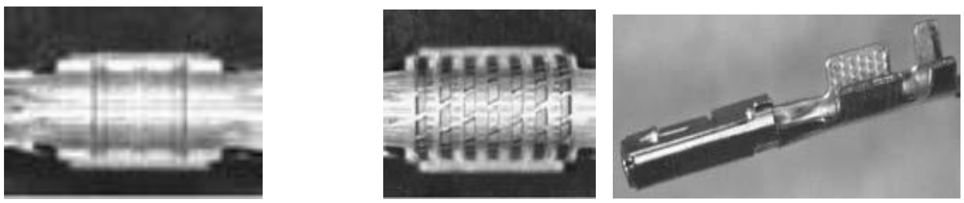


**Image 4.17-6: Aluminum Connectors, Conventional (left) and New Aluminum (right)**
*(Source: http://global-sei.com/tr/pdf/automotive/73-12.pdf)*

The study behind that paper found that a better bond could be made by adding serrations to the inside of the barrel on the connector area.

Two methods were used for anti-corrosion. Terminals for the terminal part of a wire harness generally use brass or copper alloys. This raised a concern that galvanic corrosion occurred in the connection area of the aluminum wire and the terminal depending on the external environment. In an automobile environment installation, the aluminum wire, which is adapted to the part which has a galvanic corrosion concern, needs an anti-corrosion treatment in the terminal. For the anti-corrosion method, an environmental deprivation method was developed, which blocks the contact interface of the aluminum conductor and the copper terminal from outside using a resin material. Two kinds of anti-corrosion treatments were consolidated: the molding method and the dropping method (**Image 4.17-7**).

47 *Source*: *http://global-sei.com/tr/pdf/automotive/73-12.pdf*

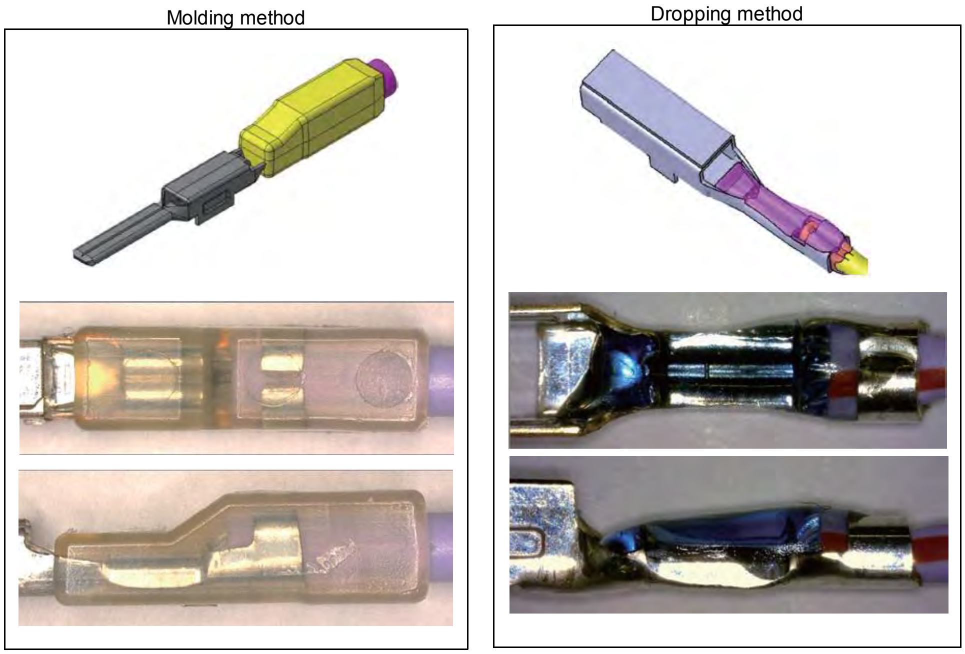



**Image 4.17-7: Terminal Anti-corrosion Treatments**
*(Source: http://global-sei.com/tr/pdf/automotive/73-12.pdf)*

The Delphi process adds a special sealant to the crimp (**Image 4.17-8**) to protect the wire connection over the life of the vehicle.

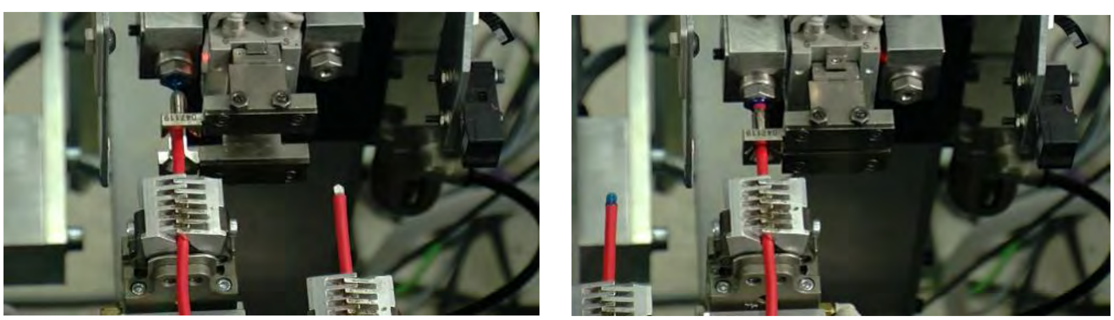


**Image 4.17-8: Aluminum Stranded Wire - Sealant**
*(Source: Delphi.com)*

The terminal is then crimped to the aluminum wire over the sealant (**Image 4.17-9**).

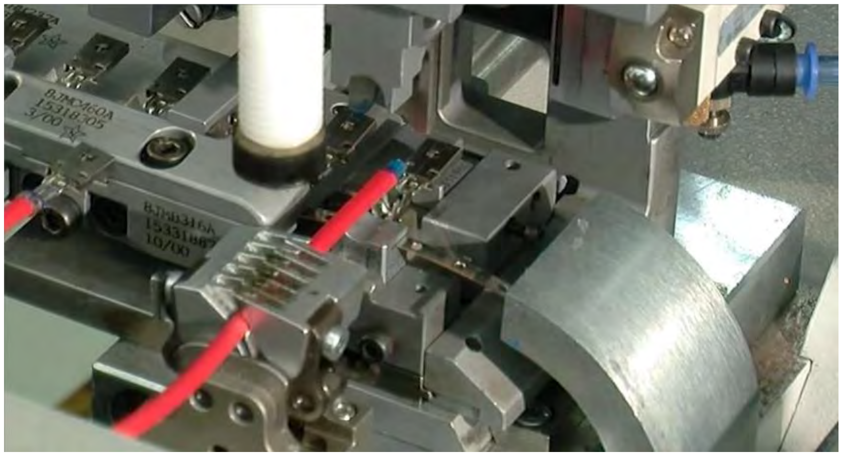


**Image 4.17-9: Aluminum Stranded Wire – Crimping**
*(Source: Delphi.com)*

A light is then applied to cure the sealant (**Image 4.17-10**).

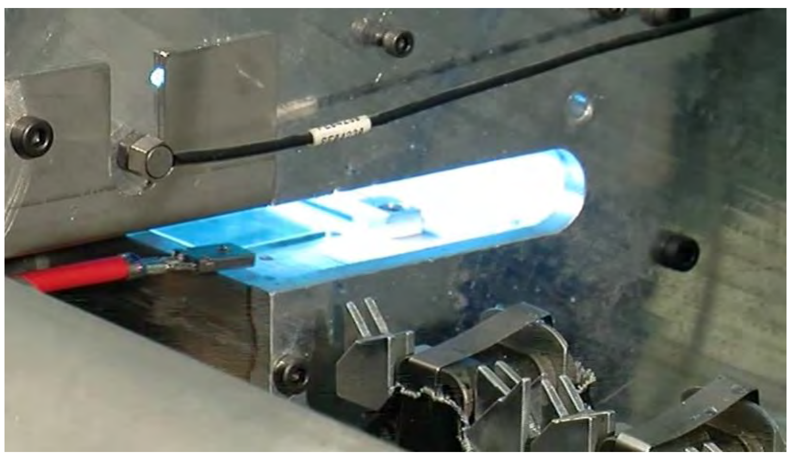


**Image 4.17-10: Aluminum Stranded Wire – Curing Process**
*(Source: Delphi.com)*

Different applications require different sizes of aluminum cable. The primary cable spans between .75 and 2.5 mm$^2$, the intermediate size is from 3 mm to 8 mm$^2$; anything over 8 mm$^2$ is power or battery cable.

**Image 4.17-11: Aluminum Stranded Wire**
*(Source: Delphi.com)*

Delphi has also done real world testing on fleet vehicles. For example, Delphi has added 60% aluminum cables into a 2011 SUV. Delphi also added aluminum cables into police cars in Maine and taxi cabs in Florida to gather information on how aluminum cable preforms in cold and warm weather. The fleet test vehicles have reached almost one million miles in testing. Remote monitoring from Delphi on the performance of the aluminum cables provided real time feed back to the Delphi engineering team, which will help in the development of future aluminum wire harnesses.

Other work being done on connectors is from the Scientists of the chairs for High Voltage Technology and Power Transmission and for Metal Casting and Forming, in cooperation with the respective departments of the BMW Group, developed an innovative aluminum-based electrical connection concept in the project LEIKO (**Image 4.17-12**).

**Image 4.17-12: Lab Version of LEIKO Aluminum Power Plug**
*(Source: http://www.greencarcongress.com/2011/02/tum-20110207.html)*

A sheet metal cage, which is an electromagnetic compatibility requirement, enhances the mechanical stability of the plug and guarantees the long-term support of the contact pressure spring. Since the necessary contact force is no longer provided by the contact elements themselves, the aluminum problematic creep behavior turns into a contact stabilizer and, thus, a positive property. This, in turn, guarantees a constant contact force over a lifetime of 10 years.

According to Professor Udo Lindemann at the Institute of Product Development at TUM (Technische Universität Munchen), "We expect the high-voltage on-board systems of most electric vehicles to be based on aluminum by 2020. Aluminum will find its way into low-voltage on-board systems as well, because the price of copper will rise significantly with increasing demand."[48]

Other connectors in development or in production include the Materion Corporation Automotive Connectors, aluminum combined with copper (**Image 4.17-13**).


**Image 4.17-13: Aluminum Stranded Wire**
*(Source: http://materion.com/Technologies/InlayCladding/InlayCladding-AutomotiveConnectors-AluminumCopper.aspx)*

The growing use of aluminum in automotive wire harnesses and components has created new challenges for traditional connectors. Overcoming the mechanical and galvanic mismatch of joining aluminum with copper devices requires a new approach to connector design.

Technical Materials' copper aluminum dovetail clad is a drop-in solution to stamping this new family of connectors. The internal joint between copper and aluminum ensures excellent electrical and mechanical performance. Galvanically, the internal joint is easily protected and isolated.[3]

48 http://www.greencarcongress.com/2011/02/tum-20110207.html

**Flat Wire**

Flat wire costs and weight reductions provided by Axon Cable® the range of flat cables with flat conductors which have been specially designed for cabling in all parts of the vehicle. They are made of flat copper conductors and a thermoplastic insulation which ensures perfect humidity and water resistance. Axon Cable also has a range of flat cables with round pins which can be soldered or inserted to achieve board to board interconnections.

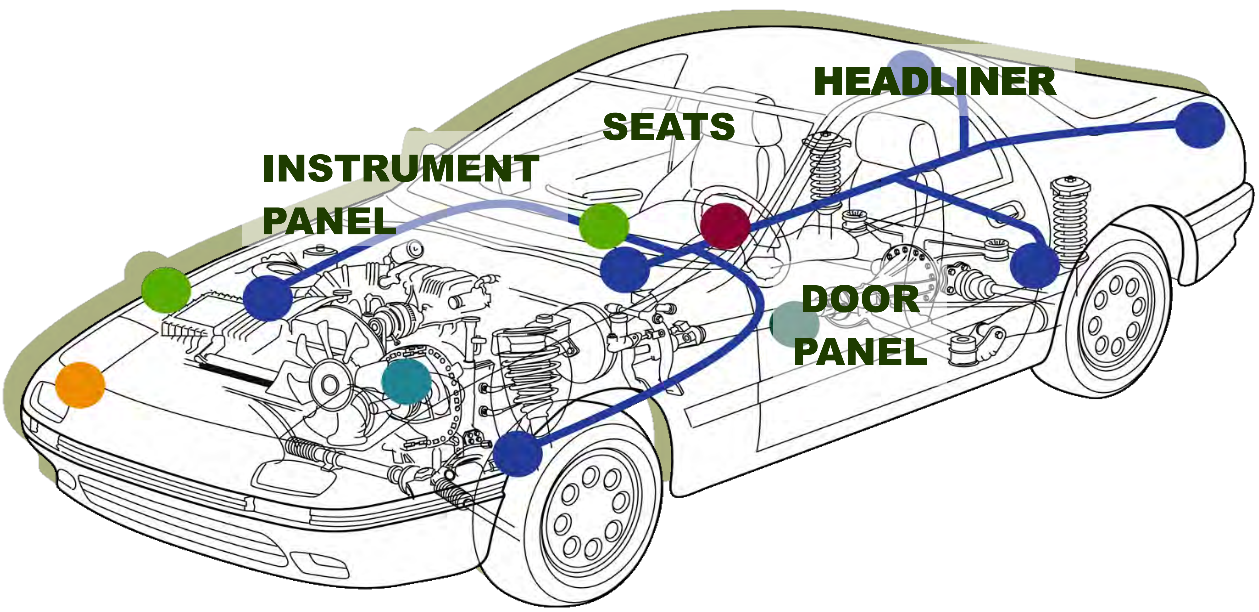



**Figure 4.17-2: Most Common Places Where Flat Cable is Used**
*(Source: Axon Cable)*

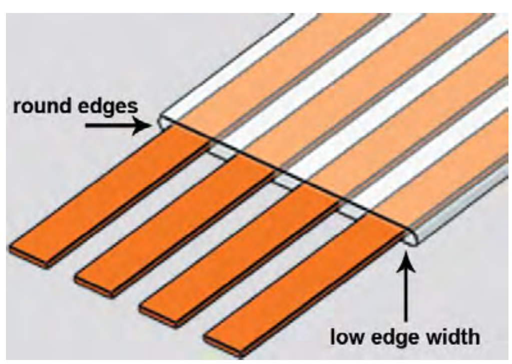



**Figure 4.17-3: Extruded FFC, with Round Edges and Low Edge Width**
*(Source: http://multimedia.3m.com/mws/mediawebserver)*

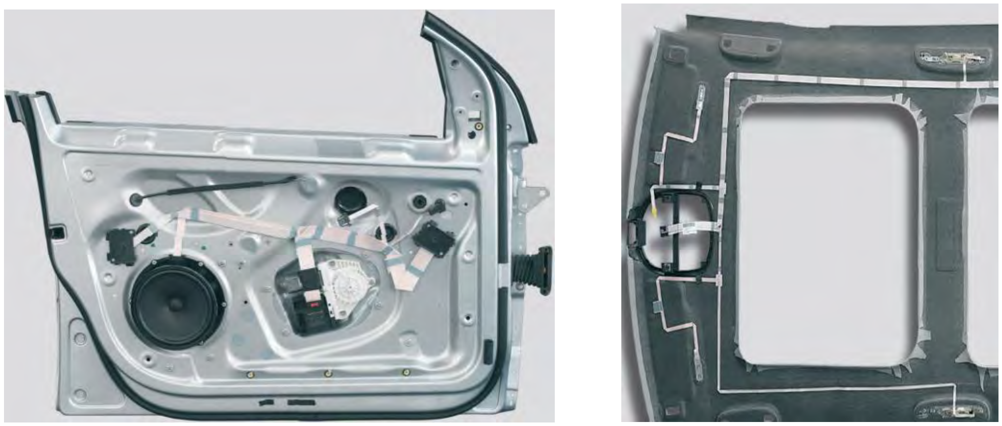


**Image 4.17-14: Flat Wire in Door (left) and Headliner (right) Applications**
*(Source: http://multimedia.3m.com/mws/mediawebserver)*

Using flat wire for some wire harness applications is a good option, such as in the headliner, doors or in the seats. Flat wire has distinct advantages:

- Weight savings potential. Thin insulation allows for conductor gauge reduction
- Lower overall systems cost, due to pre-defined positions of connectors and housings (shortened assembly time)
- Only two material components (no adhesive, only copper and extrusion material)
- Matrix technology for optimized layout (multiple usage of individual conductors)
- Reduction of connectors (direct contacting of components)
- Lower profile harness (packaging space reduction)
- Flat conductor profile (provides better heat dissipation)
- Elimination of components through integration
- Reduction in number of attachments, components, and harness coverings
- Dimensional stability/component level tolerance repeatability – 100% repeatability from one harness to the next
- Custom 3-D packaging. An application specific design ensures better fit to a substructure
- Flexibility and high ductility of FPC/FEC materials allow for 3-D form fitting to the surface profile
- Modularity Circuit patterns allows for control of electromagnetic interference and cross talk
- Reliability – Reduction in potential failure points

While there are many advantages to using flat wire harnesses, there are also disadvantages:

- Termination issues in the field

- Serviceably
- Under hood issues due to high temps
- Not good for high current items

## 42-volt systems

The future of automotive wiring is hard to predict: it could be any number of different configurations of wire or new, undiscovered materials. A few things being considered include the applications of fiber optics and carbon nanotubes, which are in the beginning stages of development. Information is therefore limited on the applications, cost, and weight reduction that they might have in future automobiles. Another option includes changing the voltage system to a 42-volt system.

Converting to 42 volts is much easier said than done: To change voltages, everything from a vehicle's lighting to charging systems would have to be redesigned. Wiring, connectors, and relays will all need to change. Some of these connector changes would already be done if moving to aluminum wire.

For the automotive industry, however, this is good news because the 42-volt systems could help reduce vehicle weight. It begins with the wiring harness. Low-voltage electricity must flow at high amperage to operate vehicle accessories, which requires thick cables and harnesses. While advantageous for the copper industry, it presents an engineering nightmare for the automotive industry. Tripling the voltage, however, effectively cuts the current by two-thirds while still providing the same power capability. For example, given that electrical power is the product of amperes multiplied by voltage, an electric motor that takes 12 amperes at 12 volts requires only 6 amperes at 24 volts, or 4 amperes at 36 volts. This enables the automotive industry to downsize wiring, shrink components, and perhaps rethink electrical architecture.

According to Charles J. Murray in his 2002 article, *Car Makers Turn Toward 42-Volt Systems*,[49] many automotive engineers were certain that automakers would soon replace the 12-volt car battery with a 42-V model. Automotive experts at the 42-Volt Automotive Systems Conference of the time predicted that half of all new vehicles would incorporate 42-V electrical architectures by 2010, and that 100% would have the technology by 2020.

Murray also noted several car manufacturers had already, or would soon introduce cars with 42-V architectures. Toyota described the development of its new Crown Mild Hybrid, which incorporates a 42-V/14-V electrical architecture. Ford Motor Company said it was working on a dual-voltage (42/14-V) station wagon, the Mondeo. Daimler, meanwhile, announced that it was using a dual-voltage design on a future Mercedes SL.

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49 *Source:* *http://www.eetimes.com/document.asp?doc_id=1227292*

While there are many advantages to a 42-volt system, there are also disadvantages. Some of these disadvantages include having to use a DC-to-DC converter, dropper resistors, battery changes, special alternator generators, packaging of units, arcing, load dump spikes, ignition system design (applicable to gasoline IC engine vehicles only), battery, and alternator – all of which need to be addressed. Therefore, at this time it cannot be stated what the cost savings or increase would be to change from the 12-volt system to the 42-volt system.

## Wire Sheathing

Wire sheathing used since the 1970s has been primarily polyvinyl chloride (PVC). With new polyphenylene oxide (PPO) and PPE polymers, manufactures are making improvements in wire sheathing cost, weight, and the recyclability.

PPO wire sheathing outperforms traditional PVC-insulated and XLPE–insulated wire. It is also friendly to the environment: PPO wire does not release the environmental pollutants characteristic of PVC–insulated wire. This fully recyclable product also meets or exceeds the electrical and thermal characteristics of PVC wire, while being smaller, lighter, and more durable. It features:

- Non–pollutant, non–toxic and recyclable since it contains no halogens, phthalates or heavy metals
- Dielectric properties of PPO enable a thinner wall thickness and outside diameter up to 45%smaller than PVC
- PPO–based wires offer the same electrical properties as PVC wires with a voltage rating of 600V

The strength and flexibility of PPO enables it to outperform PVC and other insulation materials reduced weight by up to 40%. This is due to PPO's lower specific gravity/density as compared with PVC, polyethylene (PE) and XLPE insulations

PVC is a thermoplastic polymer that is the most commonly used wire sheathing today. The advantages of using PVC are that it is inexpensive and effective. Heat, however, is an issue with PVC. PVC can only be used in 60% of automotive wiring harness applications. For high heat areas, such as the engine compartment, cross-linked polyethylene is used. PVC and cross-linked polyethylene both have environmental drawbacks as well, such as toxic halogens that can cause dioxin release and recycling issues. New products being developed by polymer manufactures will be the next generation of wire sheathing. PPO products are thinner, lighter, and stronger than PVC – plus, it is recyclable.

The PPO coating is an advanced material based on PPO and an olefin. This new flexible Noryl wire coating lacks the halogens and the potential for dioxin release – which have given PVC a bad name. PPO coating has an inherent weight advantage when the two materials are used equally.

Based on this advantage, savings come from the ability to use less PPO to match or even beat the performance of PVC. For example, on wires up to 1.5 $mm^2$, Delphi would typically use a 0.4-mm-thick PVC coating to meet its customers' requirements. The corresponding PPO thickness, by contrast, would be just 0.2 mm. PPO offers 7 to 10 times more pinch and abrasion resistance than an equal thickness of PVC. Plus, PPO, which has a glass transition temperature of 212 C, has already passed the industry's 110 C thermal tests for Class B wire. The confidence is that the material will soon pass 125 C tests as well.

The PPO weight advantage over PVC makes a strong case for its use in reducing the weight in wiring harnesses. The greater savings come from the better performance of PPO versus PVC. PPO, being thinner, reduces the overall size of the wire by 25%. This also reduces the harness bundle size.

**Table 4.17-5: Mass Reduction Ideas Selected for Electrical Wiring and Circuit Protection Subsystem**

| System | Subsystem | Sub-Subsystem | Subsystem Sub-Subsystem Description | Mass-Reduction Ideas Selected for Detail Evaluation |
|---|---|---|---|---|
| | | | | |
| 18 | 01 | 00 | Electrical Wiring and Circuit Protection Subsystem | Aluminum wire |
| | | | | GE™ PPO Sheathing |
| | | | | Steel Brkts to Composite |
| | | | | PolyOne® composite brkts |
| | | | | 3M Glass Bubbles® composite brkts |
| | | | | Flat wire form Axon Cable |

## 4.17.2 Secondary Mass Reduction / Compounding

**Table 4.17-6** contains a summary of the calculated mass reduction and cost impact for each sub-subsystem evaluated. This project recorded a system mass reduction of 8.47 kg (25.2%) at a cost decrease of $61.44 ($7.26 per kg). Furthermore, the contribution of the electrical distribution and electronic control system to the overall vehicle mass reduction was 0.35%. There are no compounding mass reductions for this system.

**Table 4.17-6: Sub-Subsystem Mass Reduction and Cost Impact for Electrical Wiring and Circuit Protection Subsystem**

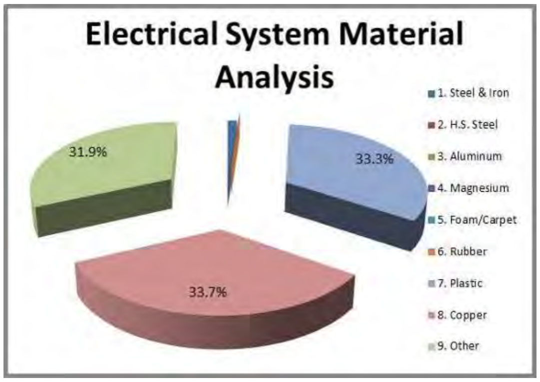
| System | Subsystem | Sub-Subsystem | Description | Net Value of Mass Reduction | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mass Reduction New Tech "kg" (1) | Mass Reduction Comp "kg" (1) | Mass Reduction Total "kg" (1) | Cost Impact New Tech "$" (2) | Cost Impact Comp "$" (2) | Cost Impact Total "$" (2) | Cost/ Kilogram Total "$/kg" | Vehicle Mass Reduction Total "%" |
| 18 | 01 | 00 | Electrical Wiring and Circuit Protection Subsystem | | | | | | | | |
| 18 | 01 | 01 | Front End and Engine Compartment Wiring | 1.50 | 0.00 | 1.50 | $15.34 | $0.00 | $15.34 | $10.25 | 0.06% |
| 18 | 01 | 02 | Instrument Panel Harness | 1.70 | 0.00 | 1.70 | $15.91 | $0.00 | $15.91 | $9.34 | 0.07% |
| 18 | 01 | 03 | Body and Rear End Wiring | 0.954 | 0.00 | 0.954 | $9.37 | $0.00 | $9.37 | $9.82 | 0.04% |
| 18 | 01 | 04 | Trailer Tow Wiring | 1.42 | 0.00 | 1.42 | $13.91 | $0.00 | $13.91 | $9.82 | 0.06% |
| 18 | 01 | 05 | Battery Cables | 0.503 | 0.00 | 0.503 | $6.94 | $0.00 | $6.94 | $13.79 | 0.02% |
| 18 | 01 | 06 | Load Compartment Fuse Box / Passive | 0.274 | 0.00 | 0.274 | -$0.80 | $0.00 | -$0.80 | -$2.92 | 0.01% |
| 18 | 01 | 07 | Interior & Console wiring | 0.667 | 0.00 | 0.667 | $0.77 | $0.00 | $0.77 | $1.15 | 0.03% |
| 18 | 01 | 08 | Frt & Rear door harness | 1.45 | 0.00 | 1.45 | $0.00 | $0.00 | $0.00 | $0.00 | 0.06% |
| | | | | 8.47 (Decrease) | 0.00 | 8.47 (Decrease) | $61.44 (Decrease) | $0.00 | $61.44 (Decrease) | $7.26 (Decrease) | 0.35% |

**(1) "+" = mass decrease, "-" = mass increase**
**(2) "+" = cost decrease, "-" = cost increase**

### 4.17.3 Electrical System Material Analysis

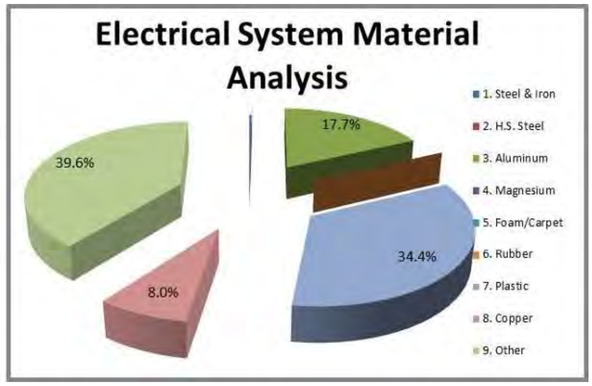
A material breakdown for the base Electrical Distribution and Electronic Control System and for the light weighted and compounded Transmission System is provided in **Figure 4.17-4**. The "Copper" content category was reduced by 25.7%, while "Aluminum" and the "Other" category increased by 17.7% and 7.7%, respectively.

**Baseline Electrical Distribution and Electronic Control System**




| | | Material Categories: |
|---|---|---|
| 1.2% | 0.399 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 0.0% | 0.000 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 33.3% | 11.184 | 7. Plastic |
| 33.7% | 11.310 | 8. Copper |
| 31.9% | 10.701 | 9. Other |
| 100% | 33.595 | TOTAL |

**Total Electrical Distribution and Electronic Control System**




| | | Material Categories: |
|---|---|---|
| 0.2% | 0.060 | 1. Steel & Iron |
| 0.0% | 0.000 | 2. H.S. Steel |
| 17.7% | 4.448 | 3. Aluminum |
| 0.0% | 0.000 | 4. Magnesium |
| 0.0% | 0.000 | 5. Foam/Carpet |
| 0.0% | 0.000 | 6. Rubber |
| 34.4% | 8.653 | 7. Plastic |
| 8.0% | 2.005 | 8. Copper |
| 39.6% | 9.961 | 9. Other |
| 100% | 25.127 | TOTAL |

**Figure 4.17-4: Calculated Electrical Distribution and Electronic Control System Baseline Material and Total Material Content**

Most of the copper and the overall weight was reduced due to the wiring being converted to aluminum.

## 4.18 Body and Frame Systems

For the EDAG analysis, the Body and Frame systems were evaluated together for many of the CAE analyses. Therefore results for both these vehicle systems are included together within this section. Also included are closures and bumper subsystems.

For some minor components (e.g. wheelhouse panel liners, body debris/protection shields, tow provisions, etc) within the Body Group A system, FEV completed the mass reduction and cost analyses. These components are not included in the EDAG presented mass and cost numbers below, though are included in the final system and vehicle values.

One assembly, the Instrument Panel Cross-Member Beam Assembly (IP XMbr Beam Assembly) was evalauated by both FEV [Section 4.3 Body System Group -B- (Interior)] and EDAG (Section 4.18 Body and Frame) The FEV evalaution considered magnesium; EDAG considered aluminum. For the primary vehicle solution the magnesium IP XMbr Beam Assembly was selected over aluminum due to its' superior dampening qualities. The estimated mass reduction was near the same (5.5 kg Mag. versus 5.8 kg Al.) with a cost premium of $20.14 for the magnesium versus aluminum beam. **The IP XMbr**

**Beam Assembly values captured in the EDAG analysis below are for reference only. They are not included in the final vehicle solution.**

The results are presented in the order the work was completed following the four-phase methodology as discussed in **Section2.3**.

### 4.18.1 Phase 1: Silverado 2011 Baseline Generation Results

As part of the Phase 1 work **(Figure 4.18-1),** system and subsystem masses were recorded during the teardown and FEA model creation. Component materials and gauges were determined and used to support the construction of the CAE models. As part of the last step in Phase 1, FEA Model Validation, CAE models where compared and correlated to physical parts using torsion and bending stiffness measurements.

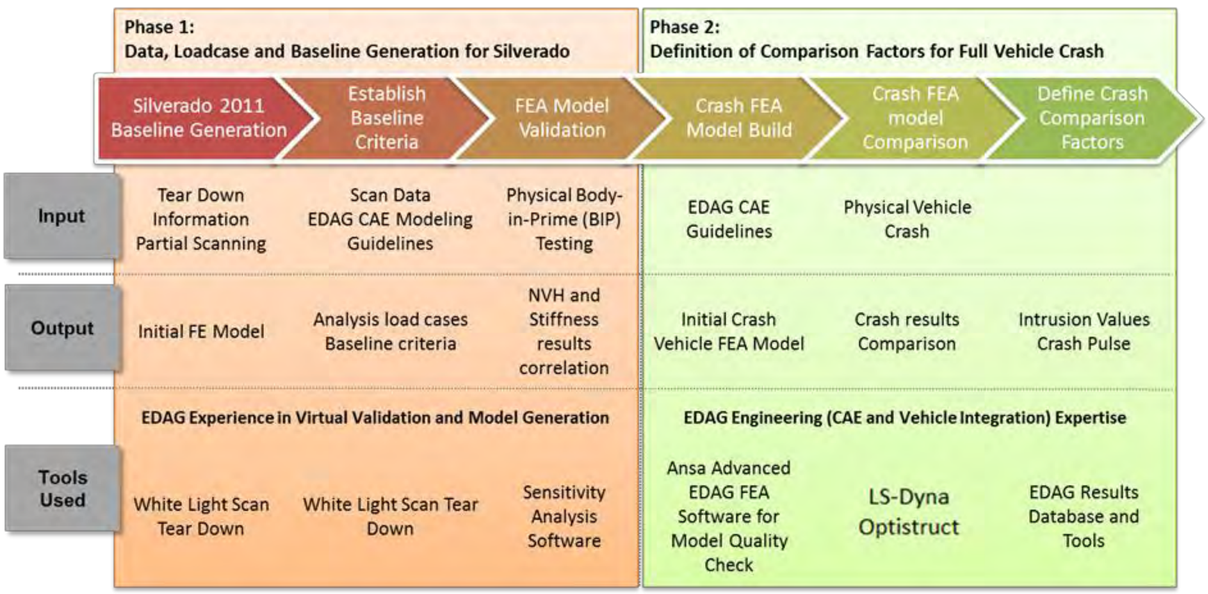



**Figure 4.18-1: Project Tasks Phase 1 and Phase 2**

#### 4.18.1.1 Baseline Component Weights, Materials and Gauges

Following completion of the Phase 1 teardown and CAE modeling building, the mass for each baseline component and assembly included in the body and frame analysis were captured (**Table 4.18-1**).

**Table 4.18-1: Mass of Baseline Body and Frame Components and Assemblies**

| Silverado Model | | |
|---|---|---|
| System | | Baseline Model Mass (Kg) |
| Box Assembly Pick-Up | | 108.3 |
| Frame Assembly | | 242.0 |
| Cabin | | 207.2 |
| Panel Fender Outer LH | | 14.9 |
| Panel Fender Outer RH | | 14.0 |
| Radiator Structure | | 12.9 |
| IP XMbr Beam Assembly | | 12.1 |
| Extra Cabin - Radiator Support | | 12.1 |
| | **Sub-Total** | **623.5** |
| Bumper Front | | 28.5 |
| Bumper Rear | | 19.9 |
| Hood Assembly without Hinges | | 22.7 |
| Door Assembly Front LH | | 29.0 |
| Door Assembly Front RH | | 28.9 |
| Door Assembly Rear LH | | 22.0 |
| Door Assembly Rear RH | | 22.2 |
| Cargo Box Gate | | 18.8 |
| | **Sub-Total** | **192.0** |
| | **Total Mass** | **815.5** |

**Figure 4.18-2** and **Figure 4.18-3** indicate the gauge and material grade maps of the baseline frame, respectively.


**Figure 4.18-2: Gauge Map of Baseline Frame (mm)**

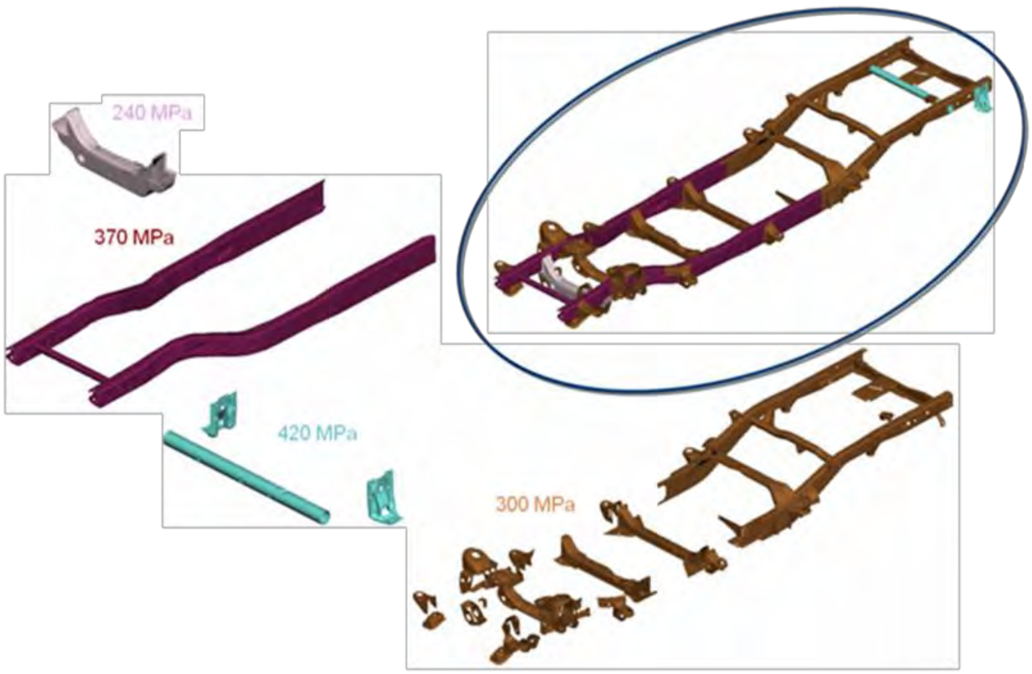



**Figure 4.18-3: Material Map of Baseline Frame**

**Figure 4.18-4** and **Figure 4.18-5** indicate the gauge and material grade maps of the baseline cabin, respectively.

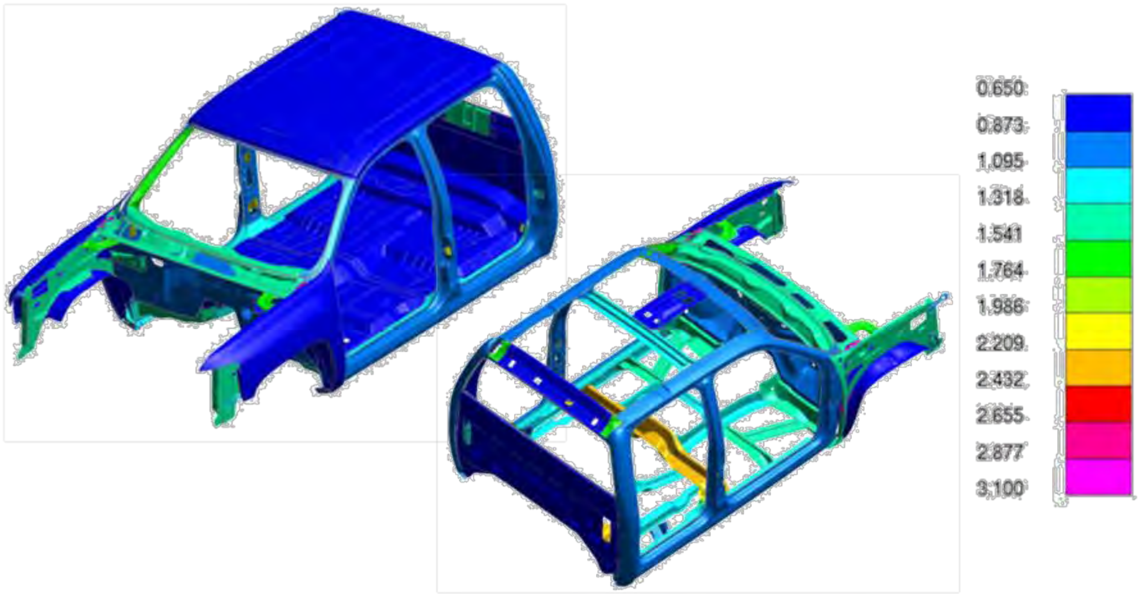



**Figure 4.18-4: Gauge Map of Baseline Cabin (mm)**

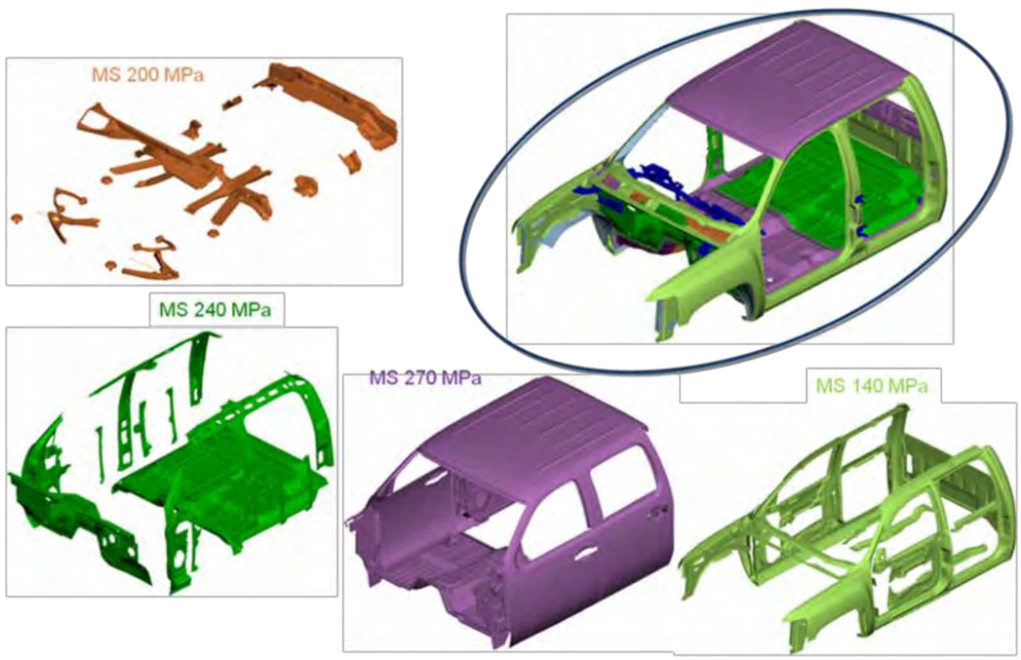



**Figure 4.18-5: Material Map of Baseline Cabin**

**Figure 4.18-6** and **Figure 4.18-7** indicate the gauge and material grade maps of the baseline cargo box, respectively.

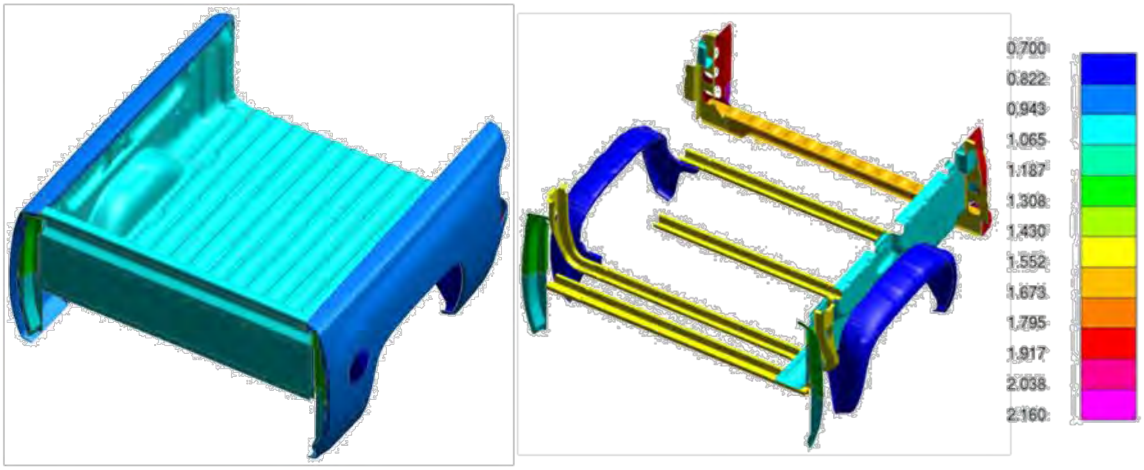



**Figure 4.18-6: Gauge Map of Baseline Cargo Box**

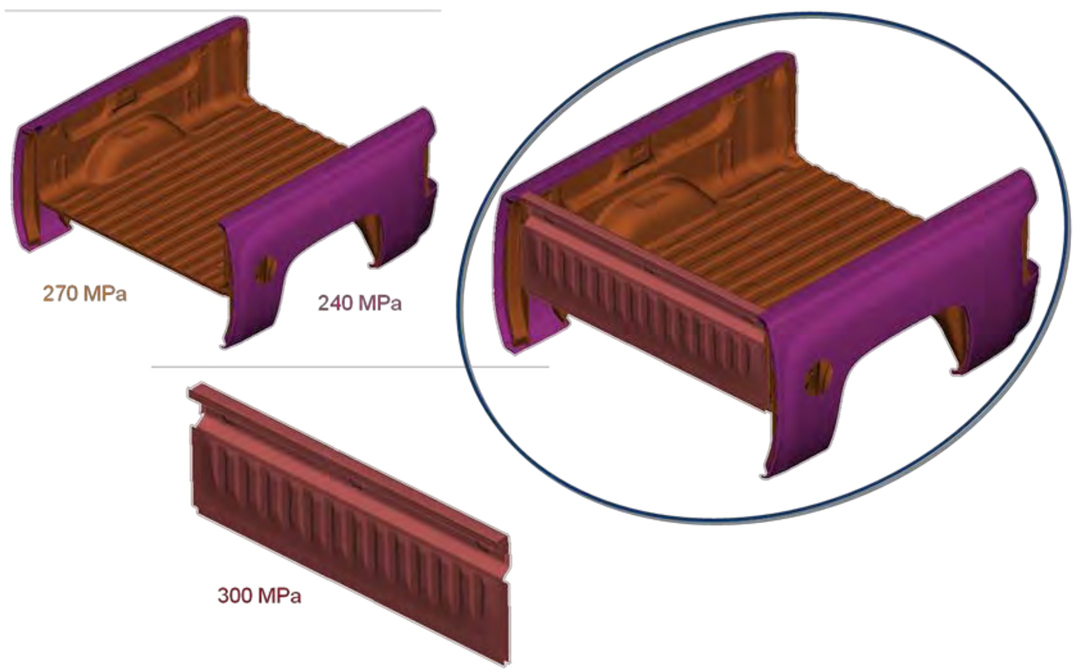



**Figure 4.18-7: Material Map of Baseline Cargo Box**

**Figure 4.18-9** and **Figure 4.18-10** indicate the gauge and material grade maps of the baseline front bumper, respectively.

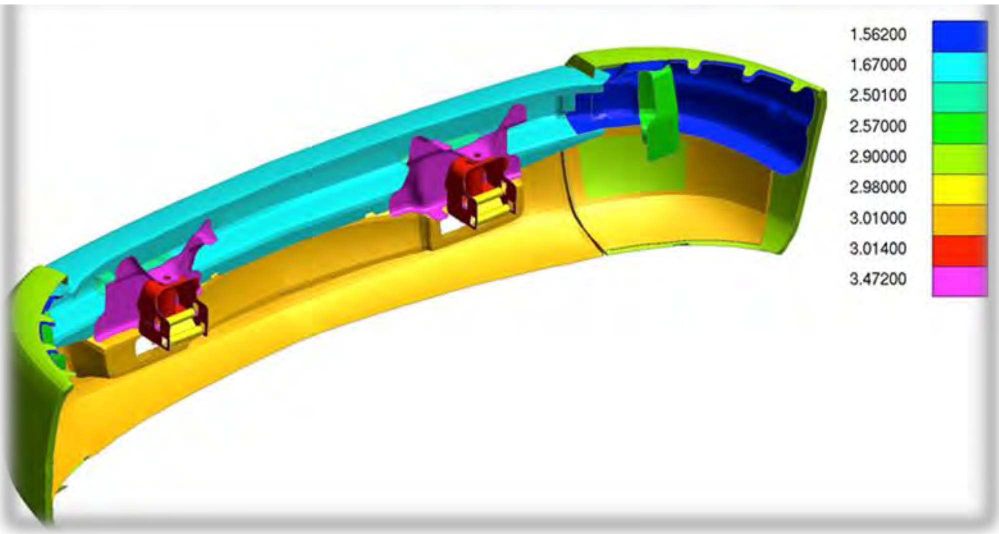



**Figure 4.18-8: Gauge Map of Baseline Front Bumper (mm)**

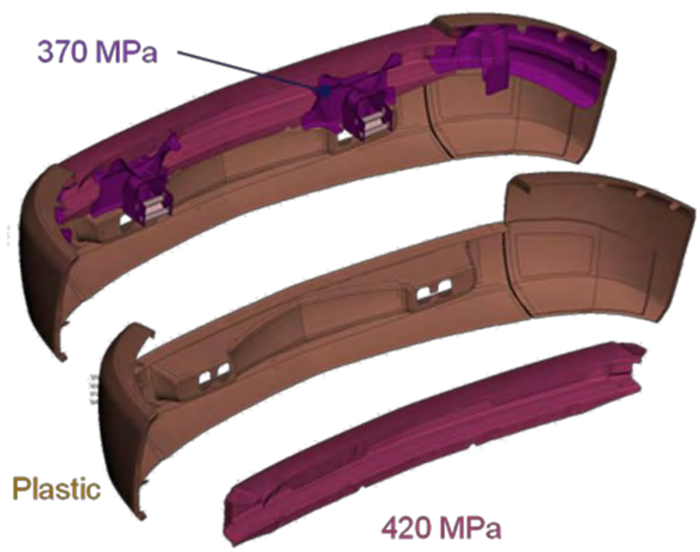



**Figure 4.18-9: Material Map of Baseline Front Bumper**

**Figure 4.18-10** and **Figure 4.18-11** indicate the gauge and material grade maps of the baseline rear bumper, respectively.

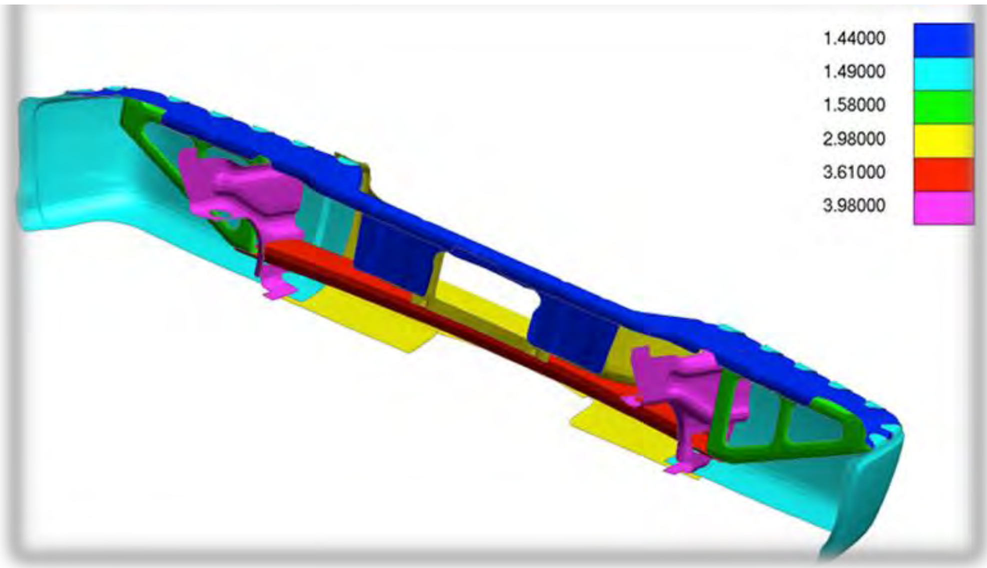



**Figure 4.18-10: Gauge Map of Baseline Rear Bumper (mm)**

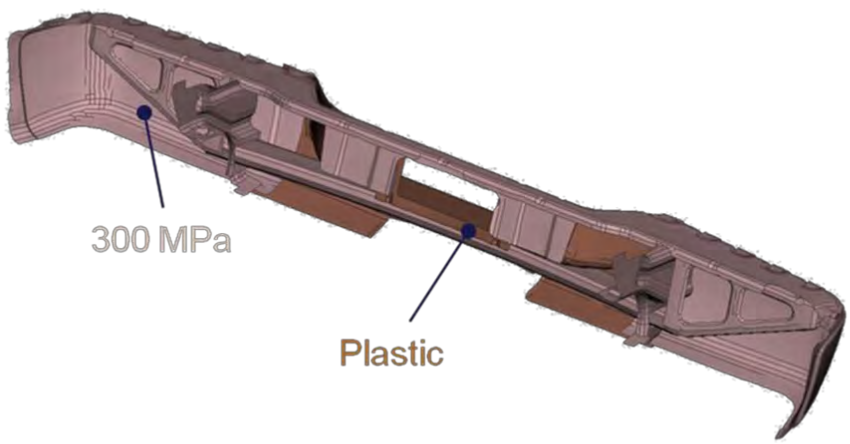



**Figure 4.18-11: Material Map of Baseline Rear Bumper**

**Figure 4.18-12** and **Figure 4.18-13** indicate the gauge and material grade maps of the baseline closures (doors, hood and tailgate), respectively.

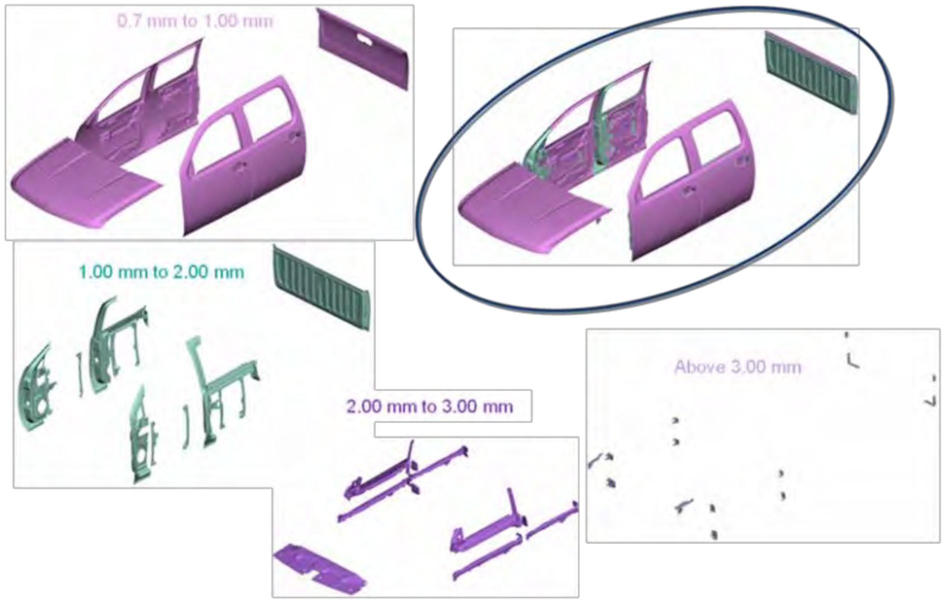



**Figure 4.18-12: Gauge Map of Baseline Closures (mm)**

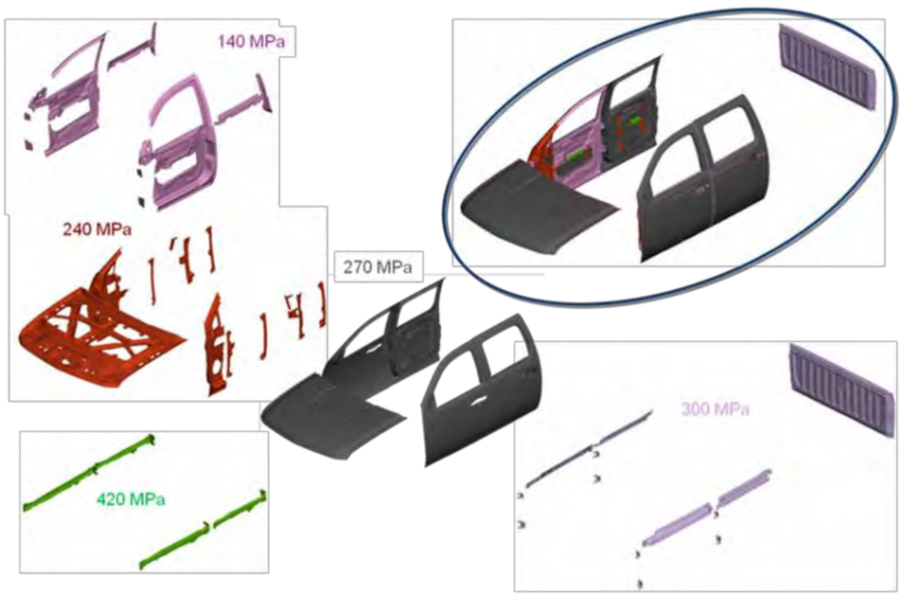



**Figure 4.18-13: Material Map of Baseline Closures**

**Figure 4.18-14** and **Figure 4.18-15** indicate the gauge and material grade maps of the baseline Instrument Panel (IP) cross member, respectively.

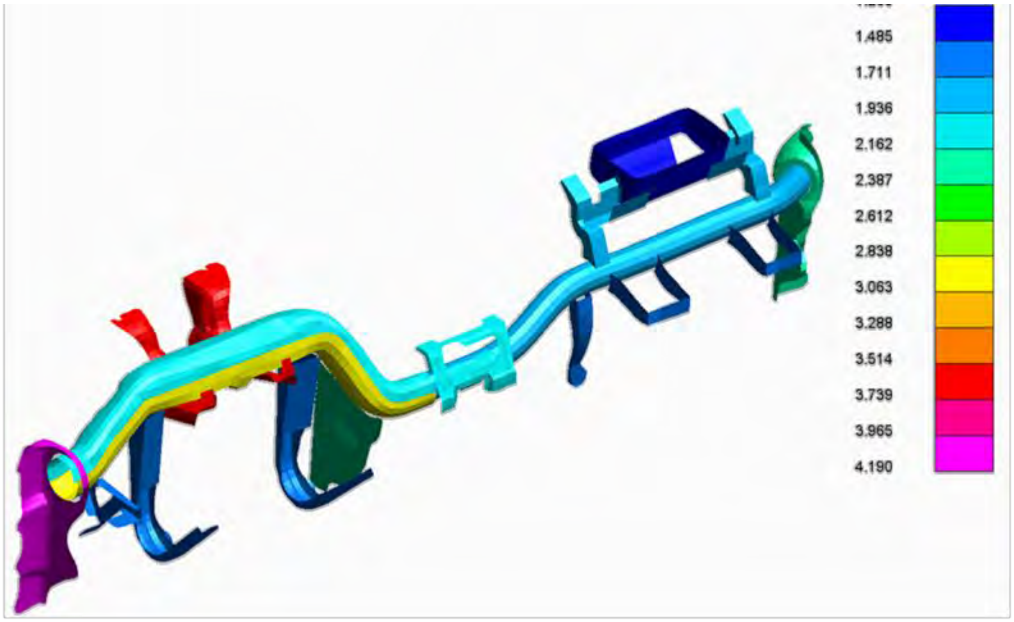



**Figure 4.18-14: Gauge Map of Baseline IP Cross Member (mm)**

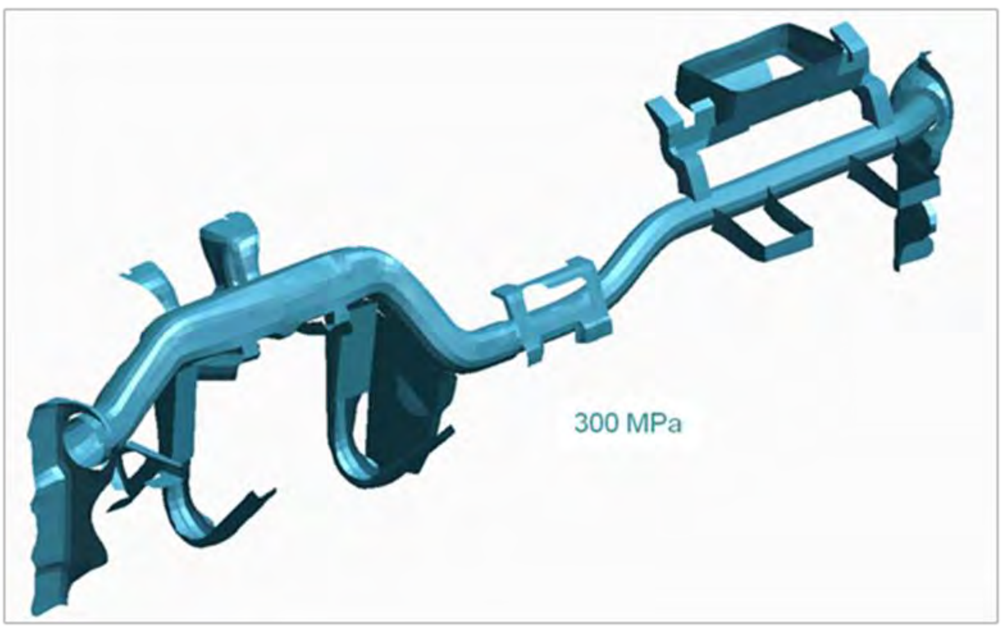



**Figure 4.18-15: Material Map of Baseline IP Cross Member**

**Figure 4.18-16** and **Figure 4.18-17** indicate the gauge and material grade maps of the baseline radiator support (structure, extra cabin support) respectively.

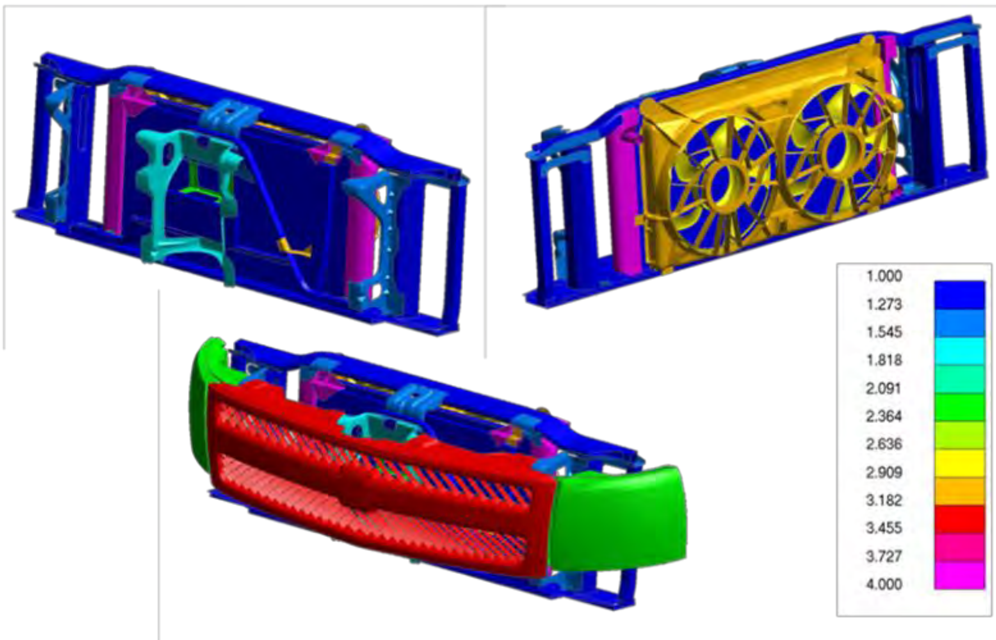



**Figure 4.18-16: Gauge Map of Baseline Radiator Support (mm)**

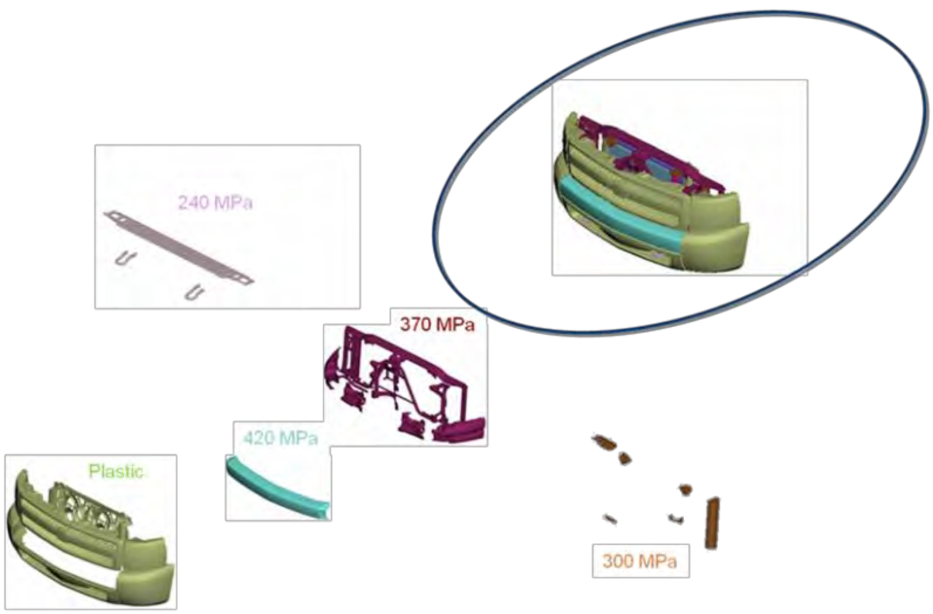



**Figure 4.18-17: Gauge Map of Baseline Radiator Support (mm)**

#### 4.18.1.2 Baseline FEA Model Validation – NVH Results

The following section contains torsional and bending stiffness comparisons between actual vehicle measurements and EDAG's baseline CAE models. The frame, cabin and cargo box were analyzed separately and then the body on frame. The criterion for acceptance was the CAE NVH model results could not be less than 5 percent of the actual test results. The CAE NVH results however could be higher than the test results as greater stiffness values were considered acceptable.

### Frame Correlation Summary

The correlations of the CAE test results of the frame NVH load cases are shown in **Table 4.18-2**. The data in the table shows the initial FE model correlated well with the test vehicle and thus was qualified as EDAG CAE baseline model for the remaining NVH load cases.

**Table 4.18-2: Frame NVH Model Correlation Comparison with Test Data**

| Description | Torsion Stiffness (KN*m/rad) | Bending Stiffness (N/mm) | Comments |
|---|---|---|---|
| **Actual Test Results (Frame)** | 180 | 3,070 | Physical Test of 2011 Silverado |
| **EDAG CAE Model Baseline Frame** | 190.3 | 2,983 | CAE Model of 2011 Silverado Frame same configuration as Test Vehicle |
| **Percentage of CAE Model to Actual Test Results** | 105.7% | 97.2% | Model Correlation |

### Cabin Correlation Summary

The correlation of the CAE test results of the cabin NVH load cases are shown in **Table 4.18-3.** The data shows the initial FE model correlated well with the test vehicle and thus was qualified as EDAG CAE baseline model for the remaining NVH load cases.

**Table 4.18-3: Cabin NVH Model Correlation Comparison with Test Data**

| Description | Torsion Stiffness (KN*m/rad) | Bending Stiffness (N/mm) | Comments |
|---|---|---|---|
| Actual Test Results (Cabin) | 1,020 | 7,217 | Physical Test of 2011 Silverado |
| EDAG CAE Model Baseline Cabin | 1,021.5 | 7,060 | CAE Model of 2011 Silverado Cabin same configuration as Test Vehicle |
| Percentage of CAE Model to actual Test Results | 100.2% | 97.8% | Model Correlation |

## Cargo Box NVH Data

No experimental NVH data was available for the standalone cargo box. This limited the cargo box CAE model validation to material gauges and mass comparisons to the actual vehicle cargo box. In addition, a review of the cargo box model NVH results (**Table 4.18-4**) was conducted by the internal team to verify the values were subjectively reasonable. The cargo box was included in the overall body and frame NVH comparison analyses (**Table 4.18-5**) supporting the cargo box model validation.

**Table 4.18-4: Cargo Box NVH Model Results**

| Study Description | Torsion Stiffness (KN*m/rad) | Bending Stiffness (N/mm) | Comments |
|---|---|---|---|
| EDAG CAE Model Baseline Cargo Box | 219.8 | 2,324.0 | CAE Model of 2007 Silverado Box same configuration as Test Vehicle |

## Body on Frame Correlation Summary

The results of the NVH simulations were compared to the 2011 Silverado actual test results.

The correlation of the CAE test results of the BOF NVH load cases are shown in **Table 4.18-5** along with the actual test results of the 2011 Silverado vehicle. The data in the table shows the initial FE model correlated within the test results range and thus was qualified as the EDAG CAE baseline model for the remaining NVH load cases.

**Table 4.18-5: BOF NVH Model Correlation Comparison with Test Data**

| Description | Torsion Stiffness (KN*m/rad) | Bending Stiffness (N/mm) | Comments |
|---|---|---|---|
| Actual Test Results (2011 BOF) | 296 | 5,602 | Physical Test of 2011 Silverado |
| EDAG CAE Model Baseline BOF | 282.3 | 5,337 | CAE Model of 2011 Silverado Cabin same configuration as Test Vehicle |
| Percentage of CAE Model to actual Test Results | 95.4% | 95.3% | Model Correlation |

### 4.18.2 Phase 2: Definition of Comparison Factors for Full Vehicle Crash

As part of the Phase 2 tasks, actual vehicle crash data was used to further refine the CAE models (**Figure 4.18-18**). Once the CAE models were with the acceptable range, as compared to actual test data, additional crash load cases were run. The crash data from all seven load cases were then used in the mass reduction optimization process.

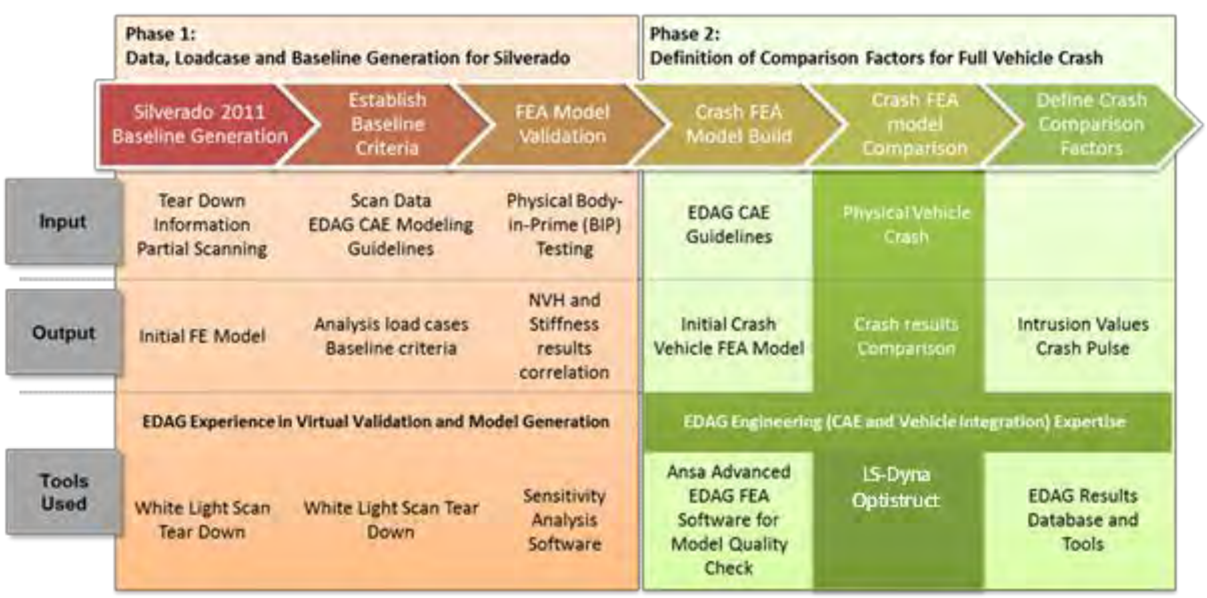



**Figure 4.18-18: Crash FEA Model Comparison**

#### 4.18.2.1 Crash FEA Model Comparison

The LS-DYNA model results (which are a hybrid of 2007 and 2011 vehicles) have been compared against three NHTSA physical tests as detailed below.

1) FMVSS 208—35mph, Flat Frontal Crash (US NCAP)

2) FMVSS 214—38.5mph, MDB Side Impact (US SINCAP)

3) FMVSS 214—20mph, 5$^{th}$ Percentile Pole Side Impact

The details of these three load cases and comparisons of the test results and CAE simulations are explained in the following section.

##### 4.18.2.1.1 <u>FMVSS 208—35mph Flat Frontal Crash (US NCAP)</u>

**Model Setup**

The frontal impact test of FMVSS 208 (US NCAP) undertaken by the NHTSA, is a full frontal flat barrier test at a vehicle speed of 35 mph (56 km/h). The corresponding NHTSA Test No. 7121[50] of a 2011 Silverado was referenced to obtain initial crash setup details. **Image 4.18-1** shows the FMVSS 208 frontal impact test setup of a 2011 Silverado.


**Image 4.18-1: FMVSS 208 35 Flat Frontal Crash Test Setup**
*(Source: EDAG)*

50 NHTSA Test No. 7121, for 2011 GM Silverado 35 flat frontal crash.

The CAE model was setup as defined in the FMVSS 208 regulation. The LS-DYNA model was created to represent the exact test initial setup, such as vehicle velocity of 35mph against a flat rigid wall barrier.

To measure passenger compartment structure integrity, data analysis points as shown in **Figure 4.18-19** were measured using the IIHS measurement protocol.

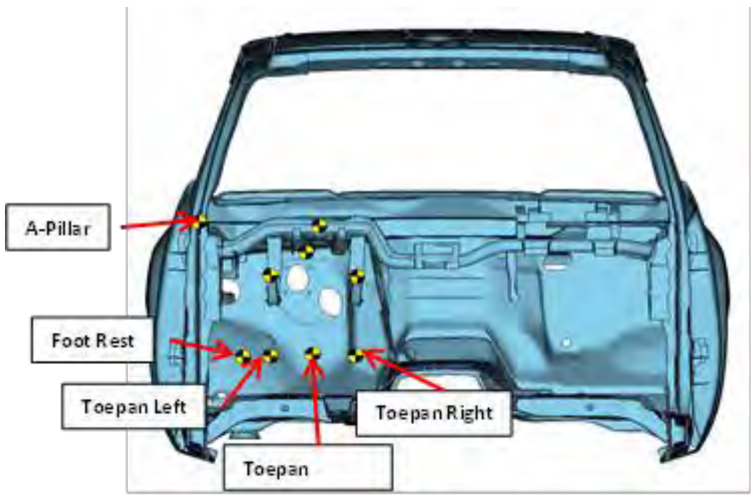



**Figure 4.18-19: Intrusion Measurement Locations**

The LS-DYNA simulation was carried out for a 150 milliseconds (ms) analysis time frame.

## Deformation Mode Comparison

There are two NHTSA tests for this configuration on the Silverado:

Test 7121 2011 4WD V8 Silverado 1500

Test 5877 2007 2WD V8 Silverado 1500

Global vehicle deformation and vehicle crash behaviors were analyzed and compared to the test photographs of the deformation modes of the 2011 Silverado. **Figure 4.18-20** through **Figure 4.18-23** show different views of the comparative deformation at 150ms (end of crash) for the 2011 Silverado versus the EDAG baseline model.

**Figure 4.18-20: Deformation Mode Comparison- Right Side View at 150ms**
*(Source: EDAG)*

**Figure 4.18-21: Deformation Mode Comparison- Front View at 150ms**
*(Source: EDAG)*

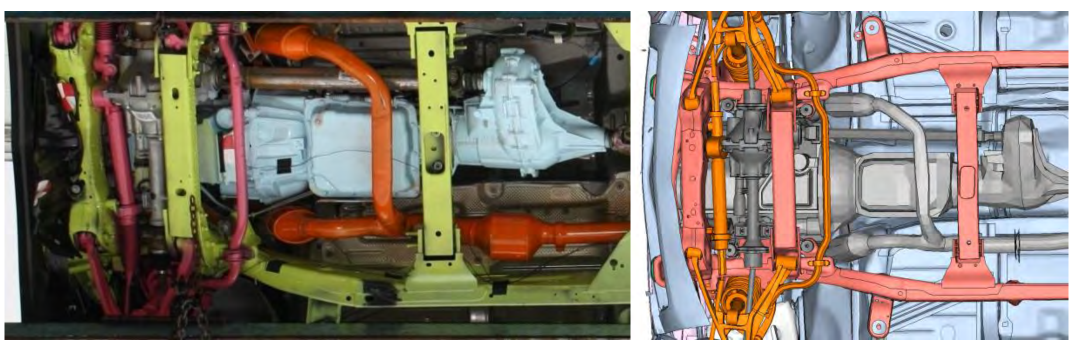


**Figure 4.18-22: Deformation Mode Comparison - Bottom View at 150ms**
*(Source: EDAG)*

**Figure 4.18-23: Deformation Mode Comparison - ISO View at 150ms**
*(Source: EDAG)*

**Figure 4.18-24** through **Figure 4.18-26** show different views of the comparative deformation at 150ms (end of crash) for the 2011 Silverado versus the EDAG baseline model.

**Figure 4.18-24: Deformation Mode Comparison- Right Side View at 150ms**
*(Source: EDAG)*

**Figure 4.18-25: Deformation Mode Comparison- Front View at 150ms**
*(Source: EDAG)*

**Figure 4.18-26: Deformation Mode Comparison - ISO View at 150ms**
*(Source: EDAG)*

### Body Pulse Comparison

**Figure 4.18-27** shows a schematic representation of the location of the pulse data measurement (accelerometer data number #1 and #2) on the test vehicle. The vehicle velocity was measured on the CAE model at the same location (rear-seat cross member).

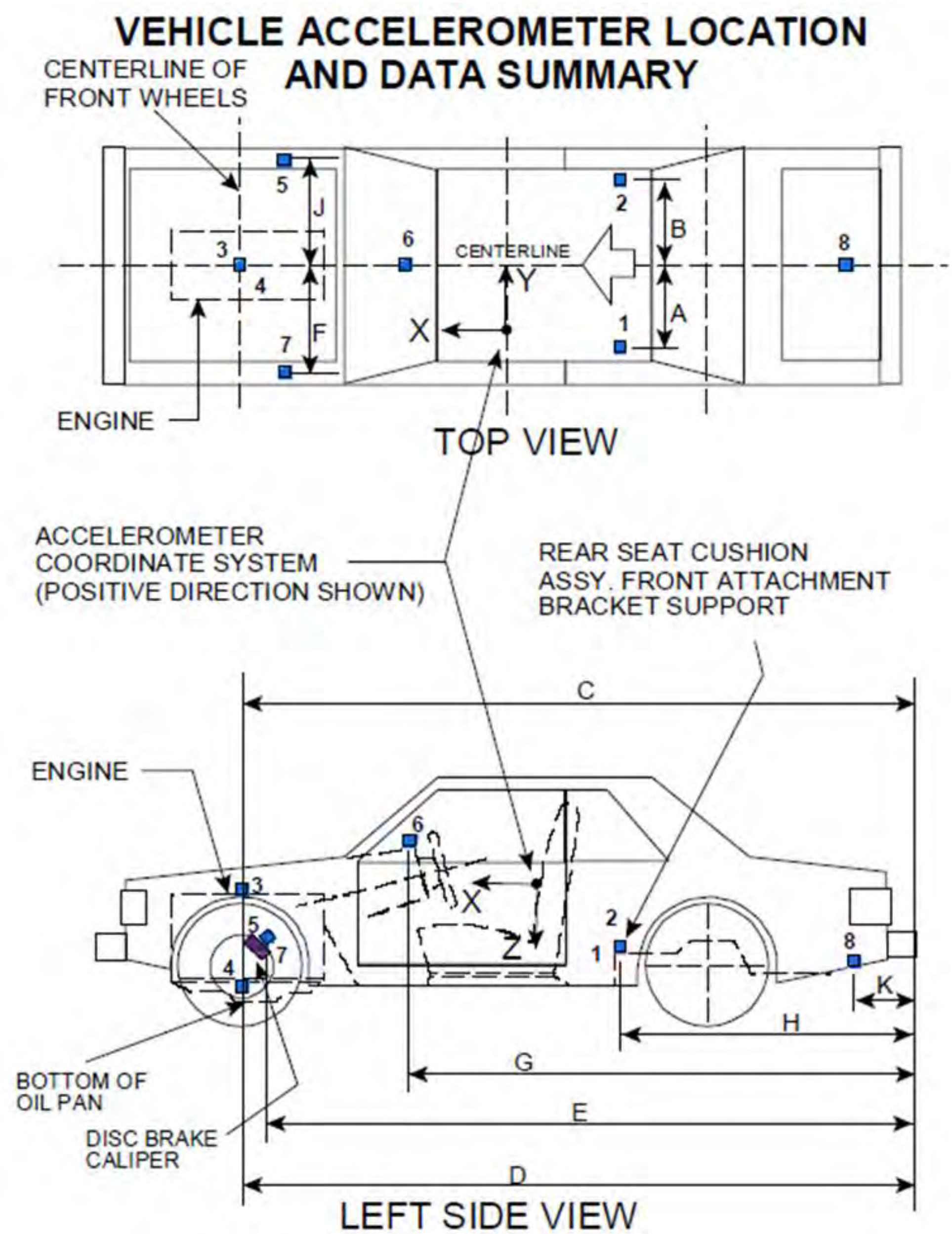



**Figure 4.18-27: Location of Vehicle Pulse Measurement**
*(Source: NHTSA)*

The vehicle acceleration pulse (in G's) calculated by averaging the driver side and the passenger side of the vehicle are shown in **Figure 4.18-28**.

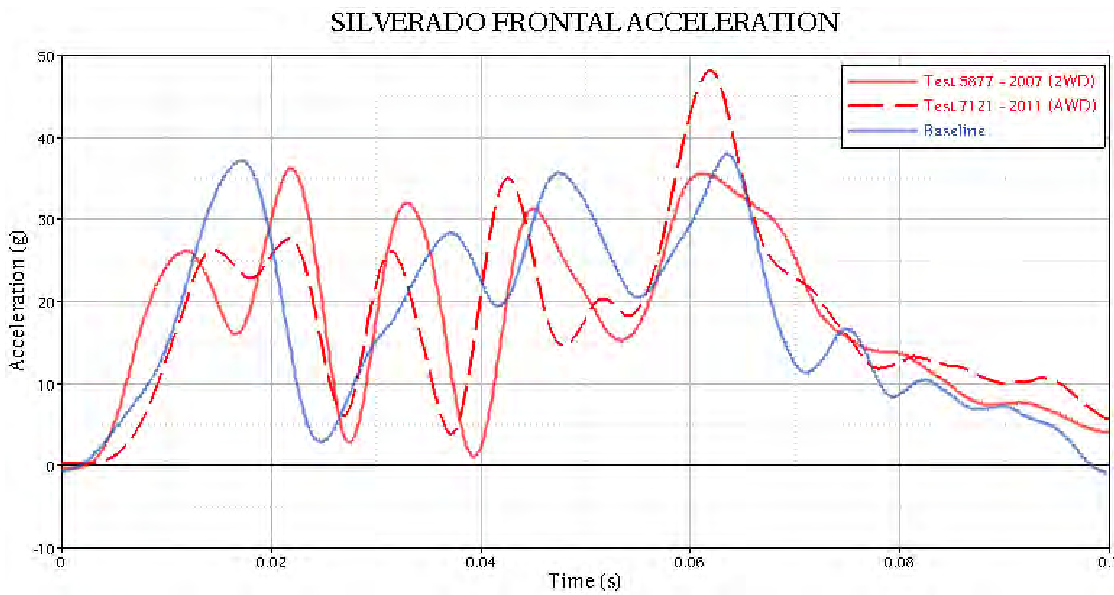



**Figure 4.18-28: CAE Baseline Model vs. Test**

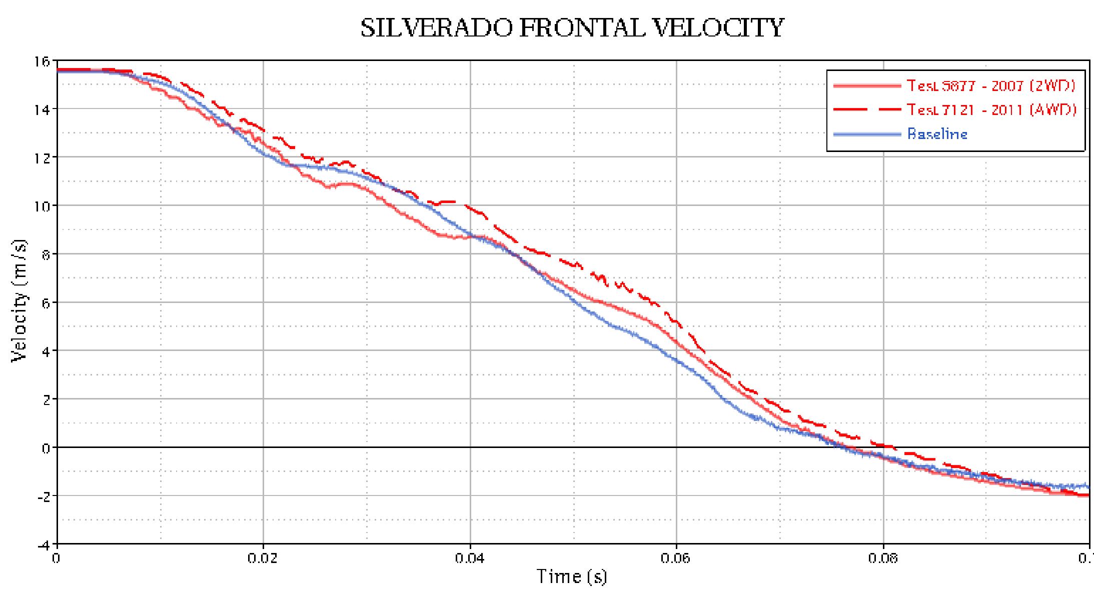



**Figure 4.18-29: CAE Baseline Model vs. Test**

## Dynamic Crush and Intrusions

Maximum dynamic crush is the total vehicle body deformation which occurs when the velocity of the vehicle (at the lower rocker in this case) is at zero before rebound. The initial static crush space of the EDAG baseline model can be estimated from the model as shown in **Figure 4.18-30**. If the front space can be crushed to 80% then this gives a total static crush space of approximately 595 mm.

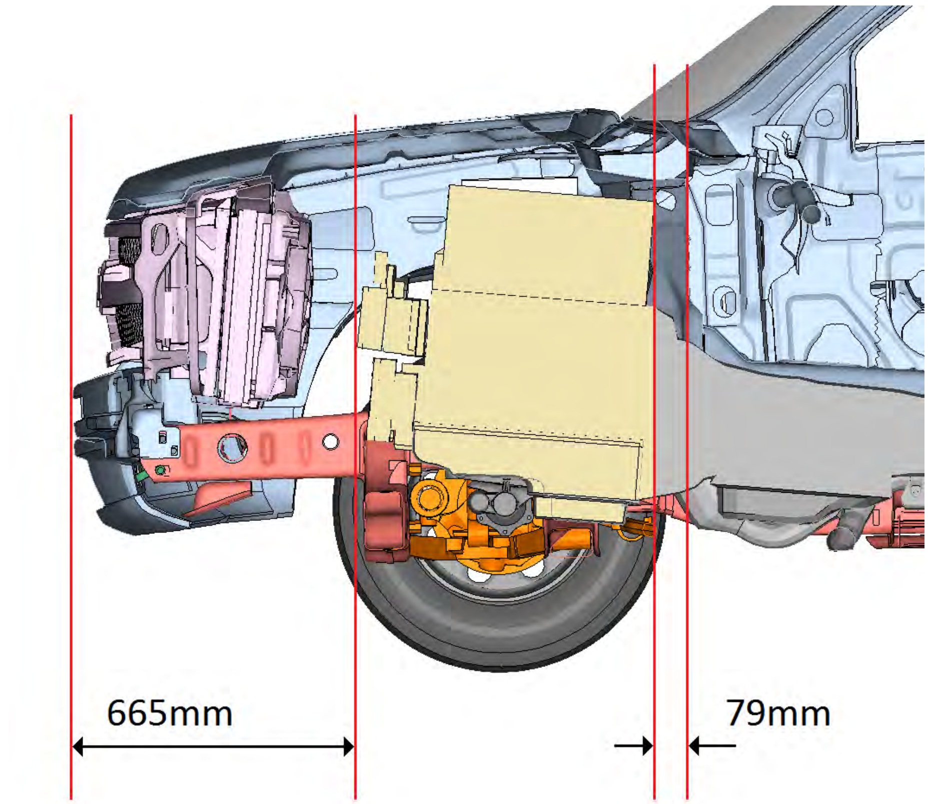



**Figure 4.18-30: Available Engine Room Crush Space before Crash Event**

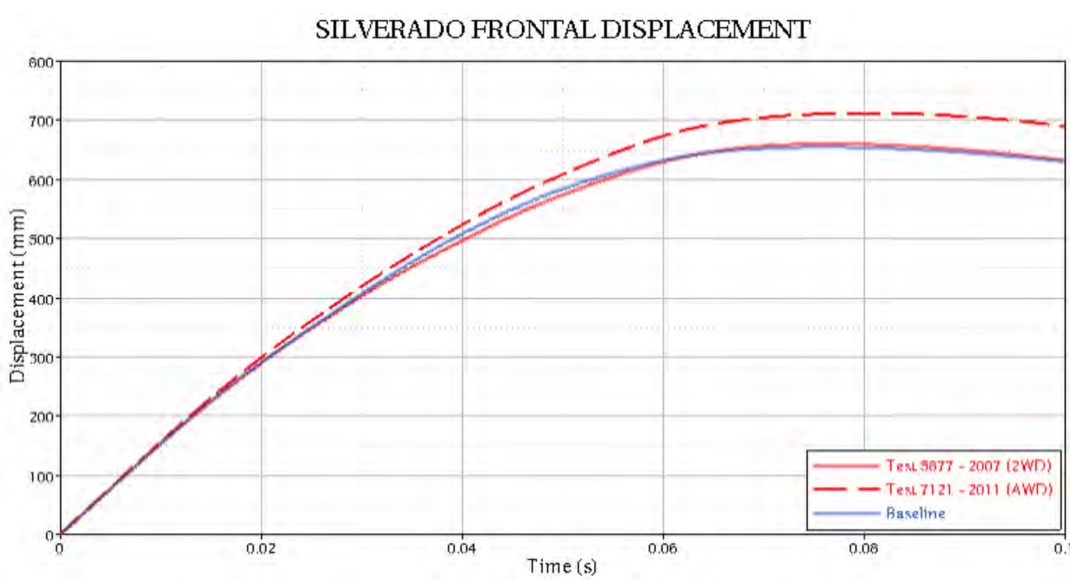



**Figure 4.18-31: CAE Baseline Model vs. Test**

**Figure 4.18-31** shows the maximum vehicle crush of 655.3mm for the baseline model compared to the test results range of 655.8 mm and 717.7 mm. A summary of performance indicators of the baseline model for the flat frontal crash loadcase is listed in **Table 4.18-6** and **Table 4.18-7**.

**Table 4.18-6: Pulse and Dynamic Crush Measurements**

| No. | Frontal Crash Measurements | Silverado Tests | 2011 GM Silverado CAE Baseline Model |
|---|---|---|---|
| 1 | Dynamic Crush (mm) | 655.8 - 717.7 | 655.5 |
| 2 | T (to zero) (ms) | 75.0-80.5 | 75.9 |
| 3 | Pulse (G's) | 37.7 - 48.1 | 37.9 |

**Table 4.18-7: Compartment Dash Intrusion Measurements**

| No. | Intrusion | Tests (mm) | Baseline (mm) |
|---|---|---|---|
| 1 | Door Opening | 6 - 4 | 6.3 |
| 2 | Driver Footrest | no data | 31.9 |
| 3 | Driver Toe Pan Left | no data | 34.5 |
| 4 | Driver Toe Pan Center | no data | 43.7 |
| 5 | Driver Toe Pan Right | no data | 44.6 |

**Table 4.18-7** lists the compartment dash intrusions measured at locations shown in **Figure 4.18-18**. Based on the analysis of the vehicle pulse, deformation mode, dynamic crush, and compartment intrusions, this model was established as EDAG's baseline target for further frontal offset loadcase iterations.

### Summary of Model Performance

The lack of detailed test data complicates the assessment of the performance; however, on a global level (velocity and displacement) the results are acceptable for the purpose of the study performed here. **Section 7.2.6** details some suggested upgrades to the LS-DYNA model if further studies are performed in the future.

#### 4.18.2.1.2 FMVSS 214—38.5mph, MDB Side Impact (US SINCAP)

**Model Setup**

The baseline crash model was compared using another crash loadcase of FMVSS214 side impact where a moving deformable barrier (MDB) with a mass of 1,370kg impacted the vehicle on the driver side with a velocity of 38.5mph (61.9 km/h) at 518 mm rearward from front axle. The corresponding NHTSA Test No. 7102 of a 2011 2WD Silverado was referenced to obtain initial crash setup and results. The CAE model was setup as defined in the FMVSS 214 regulation. Full vehicle mass, impact velocity, vehicle height, and barrier position were calibrated accordingly. A typical FMVSS 214 side impact setup with MDB is shown in **Figure 4.18-32**. The model does not include occupants or restraints, however it did include the occupant masses, which will influence the local accelerations and velocities in the door/B-Pillar.

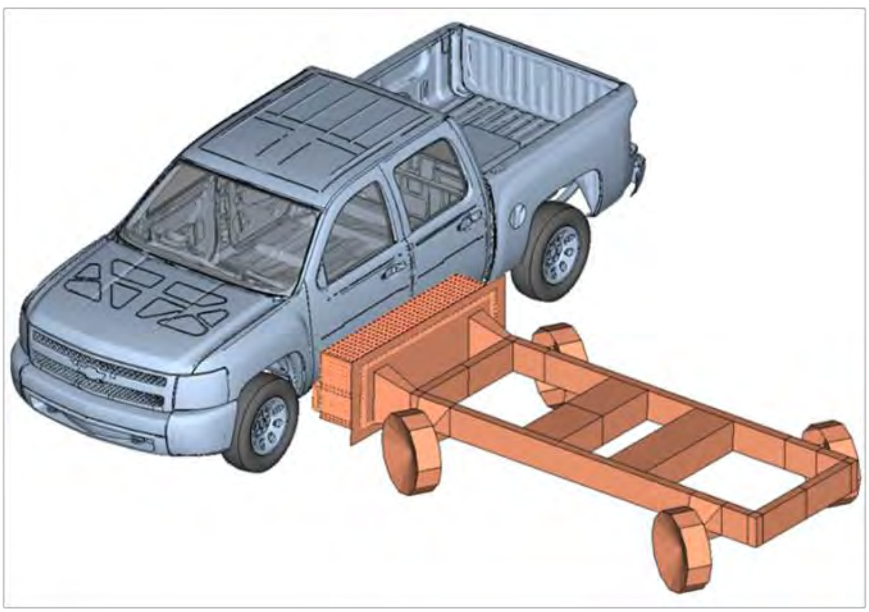


**Figure 4.18-32: FMVSS214, 38.5MDB Side Impact CAE Model Setup**
*(Source: EDAG)*

The LS-DYNA simulation was carried out for a 200ms analysis time frame. The necessary results were analyzed and compared with the test results accordingly.

**Deformation Mode Comparison**

Side-structure deformation and vehicle crash behaviors were analyzed and compared to the test photographs of deformation modes. **Figure 4.18-33** shows the pre-crash conditions for comparison purposes and **Figure 4.18-34** through **Figure 4.18-36** show the comparative deformation modes at 200ms (end of crash) in different views. By comparing the deformation modes, it can be observed the EDAG baseline model shows similar deformation modes.

**Figure 4.18-33: Side Impact Comparison- Pre-Crash**
*(Source: EDAG)*

**Figure 4.18-34: Side Impact Comparison - Post-Crash**
*(Source: EDAG)*


**Figure 4.18-35: Door Deformation Mode Comparison**
*(Source: EDAG)*

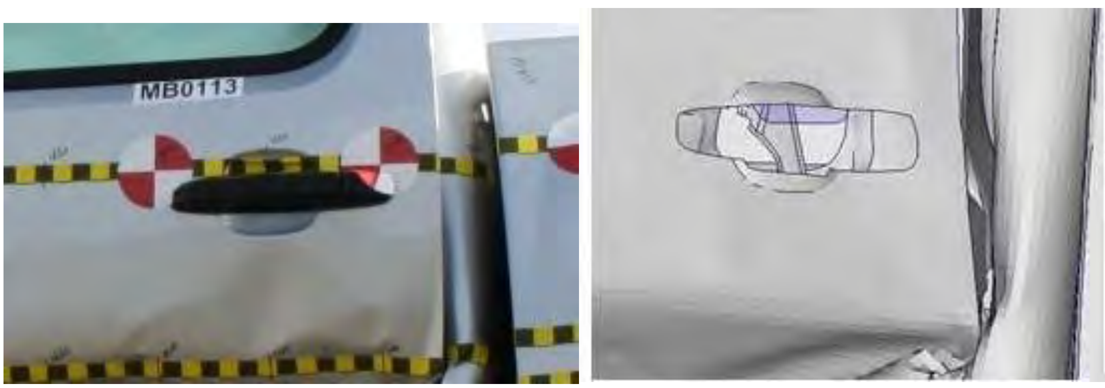



**Figure 4.18-36: Rear Door Aperture Deformation Mode Comparison**
*(Source: EDAG)*

## B-Pillar Velocity Comparison

The side impact characteristics of the baseline model were compared with the B-Pillar movement to analyze the impact pattern on the major structure that was impacted directly by the barrier. For this purpose the velocity of the side structure was measured on B-Pillar at 920 mm from the ground, as shown in **Figure 4.18-37**.

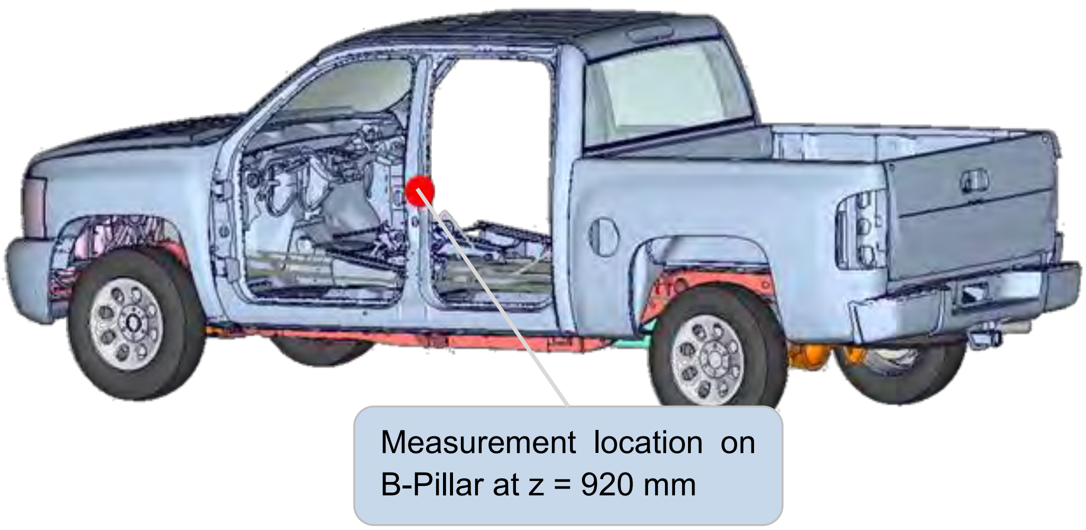



**Figure 4.18-37: B-Pillar Velocity Measurement Location**
*(Source: EDAG)*

The B-Pillar velocity is plotted with respect to that of the test results. **Figure 4.18-38** shows the side structure movement trend by B-Pillar velocity. It is observed that the baseline model shows a reasonable trend relative to the test result.

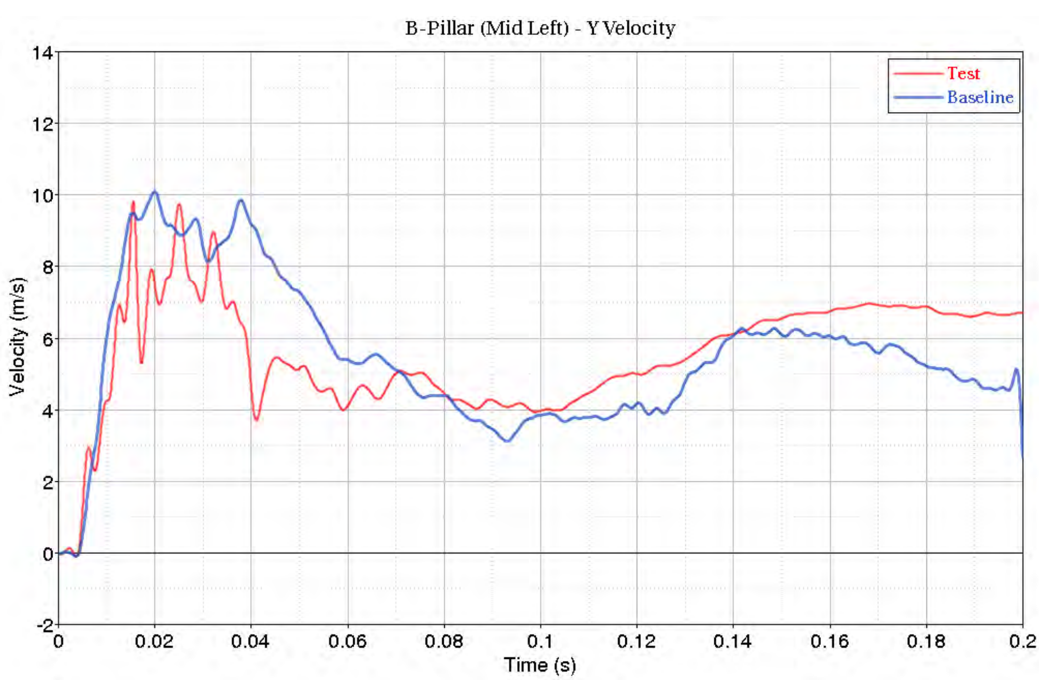
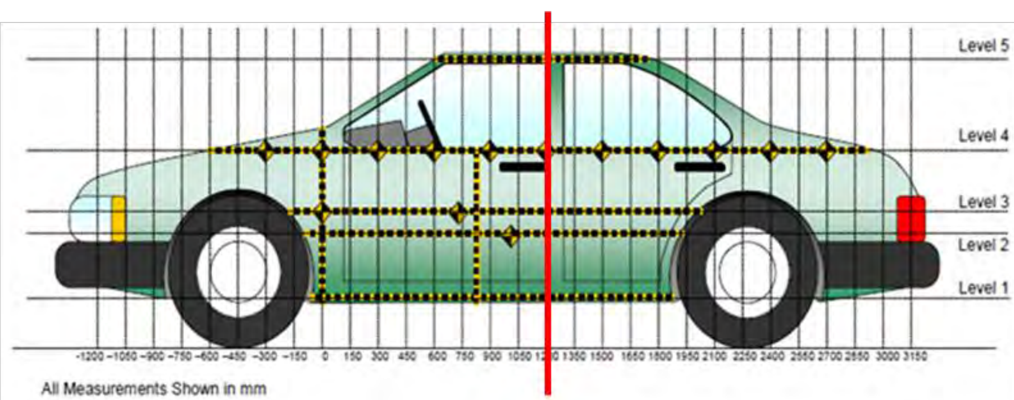



**Figure 4.18-38: B-Pillar Velocity**

## Intrusion Comparison

Another critical parameter to be compared for the MDB side impact case is the Side Structure intrusion at levels 1 through 5 of the driver-side compartment (**Figure 4.18-39**). The compartment structure intrusions were specified as intrusion numbers (**Figure 4.18-40**). The intrusion numbers represent the relative displacement with respect to an un-deformed driver-side structure. The accuracy of the intrusions was maintained by using a local vehicle coordinate system at a point on the passenger-side structure. The intrusions were measured at a longitudinal section of 1200L as shown by vertical red line in **Figure 4.18-39**. It represents the intrusion characteristics of B-Pillar areas. **Figure 4.18-40** shows a section-cut view of the B-pillar intrusion at 1200L section. The gray contour represents the un-deformed structure and the blue contour represents the deformed structure.




**LEFT SIDE VIEW**

Measurements are taken with vehicle in the as tested condition.
Measurments taken 900 mm right of impact reference.
All measurements below in mm.

| Level | Measurement Description | Height Above Ground |
|---|---|---|
| 1 | Sill Top | 406 |
| 2 | Occupant H-Point | 851 |
| 3 | Mid Door | 821 |
| 4 | Window Sill | 1171 |
| 5 | Window Top | 1774 |

All Dimensions shown in millimeters

**Figure 4.18-39: Side Structure Exterior Measuring Location and Points (Source NHTSA)**

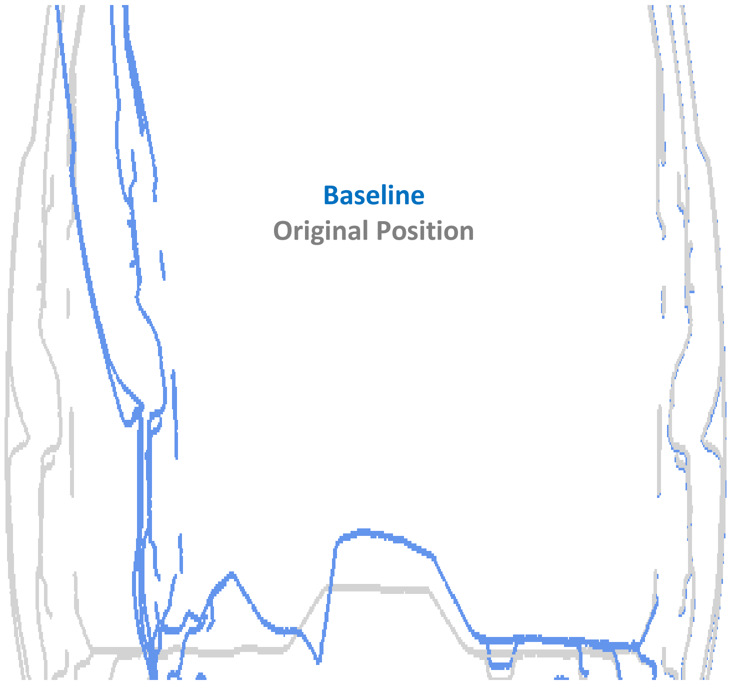



**Figure 4.18-40: Side Structure Deformation Section Cut at 1200L**

A summary of the relative intrusions of side structure of the baseline model are shown in **Table 4.18-8**.

**Table 4.18-8: Baseline, Relative Intrusions at 1200L for FMVSS 214**

| Measured Location* | Test (mm) | Baseline (mm) |
|---|---|---|
| Level-5 | 21 | 22 |
| Level-4 | 188 | 169 |
| Level-3 | 277 | 289 |
| Level-2 | 309 | 335 |
| Level-1 | 333 | 321 |
| * All measured points are taken at the vehicle exterior point | | |

**Summary of Model Performance**

The velocity profile has been compared at the B-Pillar and show an acceptable level of performance compared to the test data. The LS-Dyna model intrusions compare well to the model.

4.18.2.1.3 FMVSS 214—20 5th Percentile Pole Side Impact

**Model Setup**

The baseline crash model was compared using another side crash loadcase; of FMVSS 214 5th Percentile pole impact with pole barrier. In this loadcase, the vehicle is moved against a 2144 mm tall static rigid pole at an angle of 15thwith a velocity of 20 mph (32.2 km/h).The corresponding NHTSA Test No.7101[51] of a 2011 2WD Silverado was referenced to obtain initial crash setup and results. The CAE model was setup as defined in the FMVSS 214 regulation. Full vehicle mass, impact velocity, vehicle height, and barrier position for 5th Percentile occupant condition were calibrated accordingly. A typical FMVSS 214 side impact setup with pole barrier is shown in **Figure 4.18-41** and**Figure 4.18-42**.

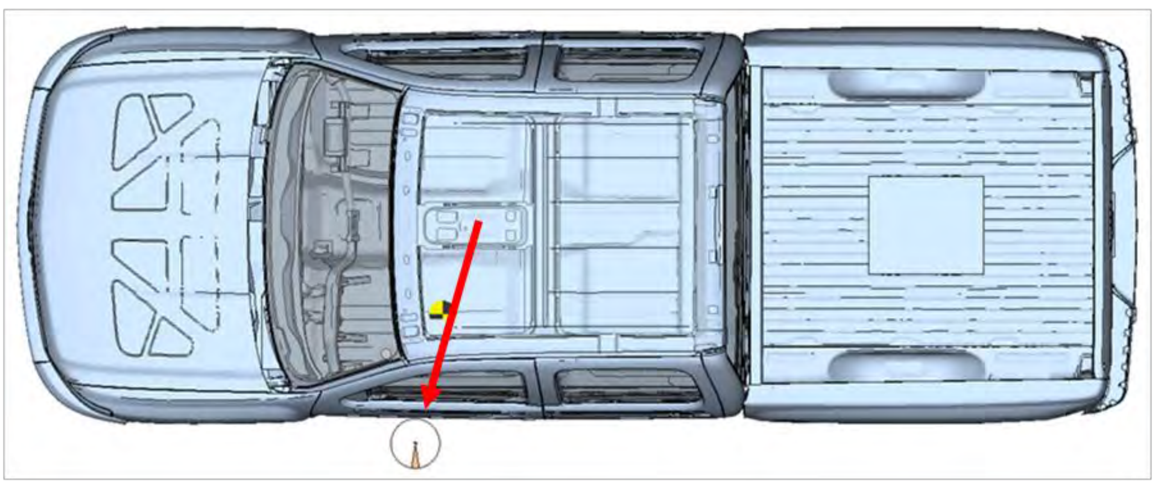


**Figure 4.18-41: FMVSS 214 5th Percentile Pole Side Impact CAE Model Setup**
*(Source: EDAG)*

51 NHTSA Test No. 7101 for 2011 GM Silverado 20 pole side impact.

**Figure 4.18-42: FMVSS 214 5th Percentile Pole Side Impact CAE Model Setup**
*(Source: EDAG)*

The LS-DYNA simulation was carried out for a 200 ms analysis time frame. The necessary results were analyzed and compared with the test results accordingly.

**Deformation Mode Comparison**

Side-structure deformation and vehicle crash behaviors were analyzed and compared to the test photographs of deformation modes. **Figure 4.18-43** shows the pre-crash conditions for comparison purposes and **Figure 4.18-44** through **Figure 4.18-46** show the comparative deformation modes at 200ms (end of crash) in different views. By comparing the deformation modes, it can be observed the EDAG baseline model shows similar deformation modes.

**Figure 4.18-43: Side Pole Impact - Pre-Crash**
*(Source: EDAG)*

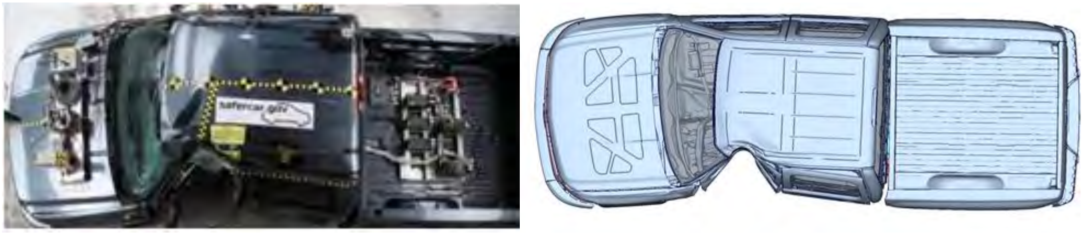


**Figure 4.18-44: Side Pole Impact - Post-Crash Top View at 200ms**
*(Source: EDAG)*

**Figure 4.18-45: Side Pole Impact - Post-Crash Side View at 200ms**
*(Source: EDAG)*

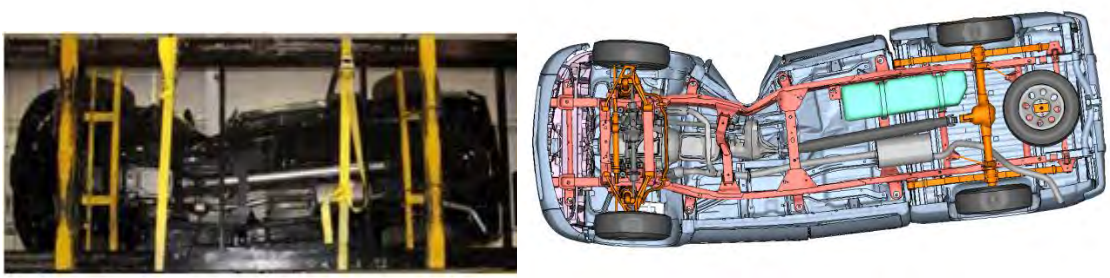


**Figure 4.18-46: Deformation Mode Bottom View at 200ms**
*(Source: EDAG)*

## B-Pillar Velocity Comparison

The side impact characteristics of the baseline model were compared with the side structure movement to analyze the impact pattern on the major structure where the vehicle impacted directly on the barrier. For this purpose the velocity of the side structure was measured on B-Pillar at 920 mm from the ground as shown in **Figure 4.18-47**.

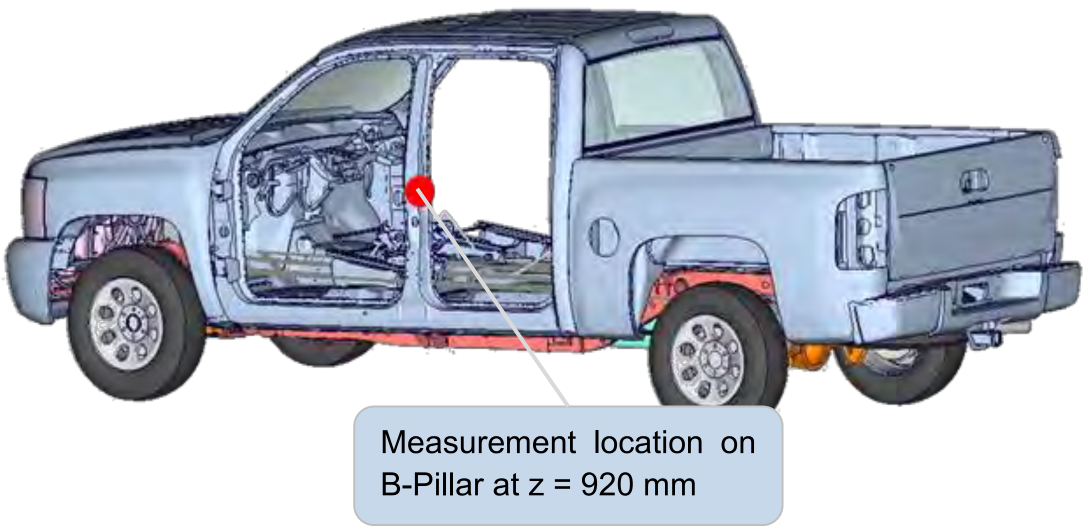



**Figure 4.18-47: B-Pillar Velocity Measurement Location**

The B-Pillar velocity is plotted with respect to that of the test results. **Figure 4.18-48** shows the side structure movement trend by B-Pillar velocity. It is observed that the baseline model shows a reasonable correlation over the test result.

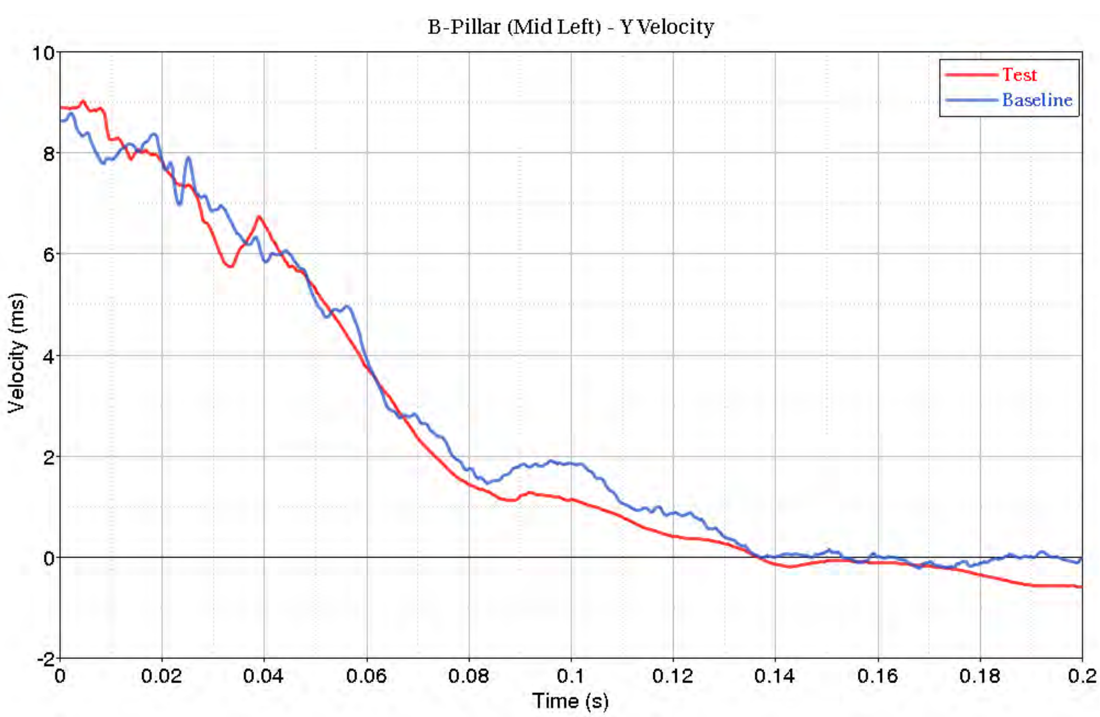



**Figure 4.18-48: B-Pillar Velocity (m/s)**

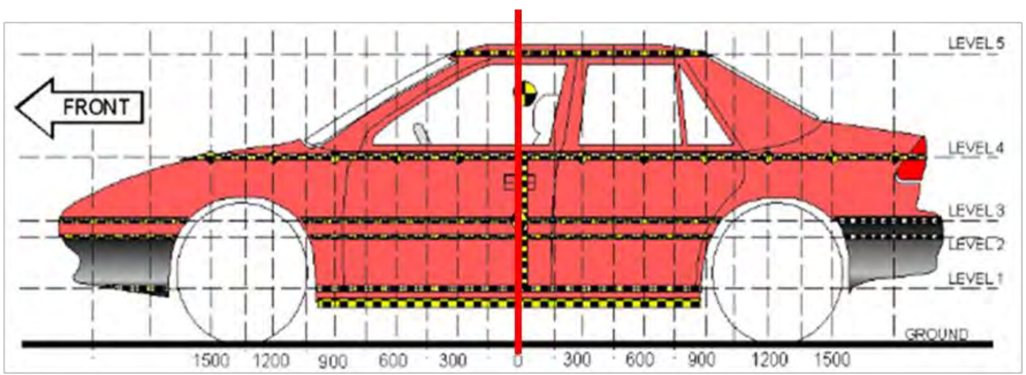
## Intrusion Comparison

Another critical parameter to be compared for the pole-side impact case is the Side Structure intrusion at the levels #1 through #5 of the driver-side compartment (

**Figure** 4.18-49). The compartment structure intrusions were specified as intrusion numbers (**Figure 4.18-50**). The intrusion numbers represent the relative displacement with respect to an un-deformed driver-side structure. The accuracy of the intrusions was maintained by using a local vehicle coordinate system at a point on the passenger-side structure. The intrusions were measured at a longitudinal section of 0L as shown by vertical red line in

**Figure** 4.18-49. It represents the intrusion characteristics of B-Pillar areas. **Figure 4.18-50** shows a section-cut view at 0L section. The gray contour represents the un-deformed structure and the blue contour represents the deformed structure.

**Figure 4.18-49: Side Structure Exterior Measuring Locations and Points (Source NHTSA)**




| Level | Measurement Description | Height Above Ground |
|---|---|---|
| 5 | Window Top | 1750 |
| 4 | Window Sill | 1180 |
| 3 | Mid Door | 840 |
| 2 | Occupant H-Point | 910 |
| 1 | Sill Top | 455 |

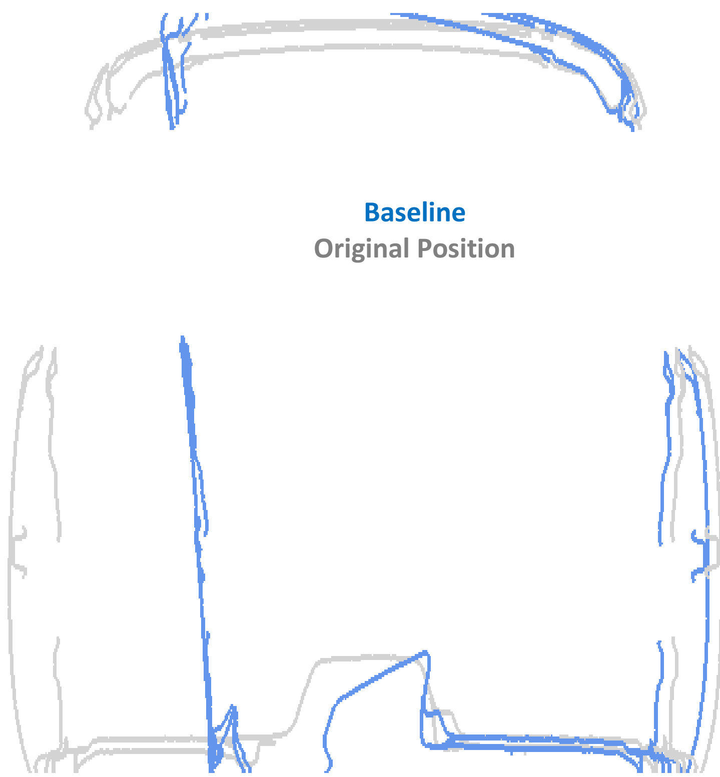



**Figure 4.18-50: Side Structure Deformation Section Cut at 0L**

A summary of the relative intrusions of side structure of the baseline model are shown in **Table 4.18-9**.

**Table 4.18-9: Baseline, Relative Intrusions at 0L for Side Pole Impact**

| Measured Location* | Test (mm) | Baseline (mm) |
|---|---|---|
| Level-5 | 297 | 241 |
| Level-4 | 530 | 492 |
| Level-3 | 588 | 546 |
| Level-2 | 583 | 553 |
| Level-1 | 527 | 510 |
| * All measured points are taken at the vehicle exterior point | | |

## Summary of Model Performance

The LS-DYNA model shows intrusions approximately 10% less than the 2011 NHTSA test. Possible explanations include:

- Lack of a damage and failure model in the front screen (windshield)
- Weld or material failure (not possible to quantify if this was significant from the data contained in the NHTSA report)
- Differences in the 2007 – 2011 Cab

The same limitations exist for the optimized model so the performance here is acceptable for the purpose of the study.

### 4.18.3 Baseline Crash Results

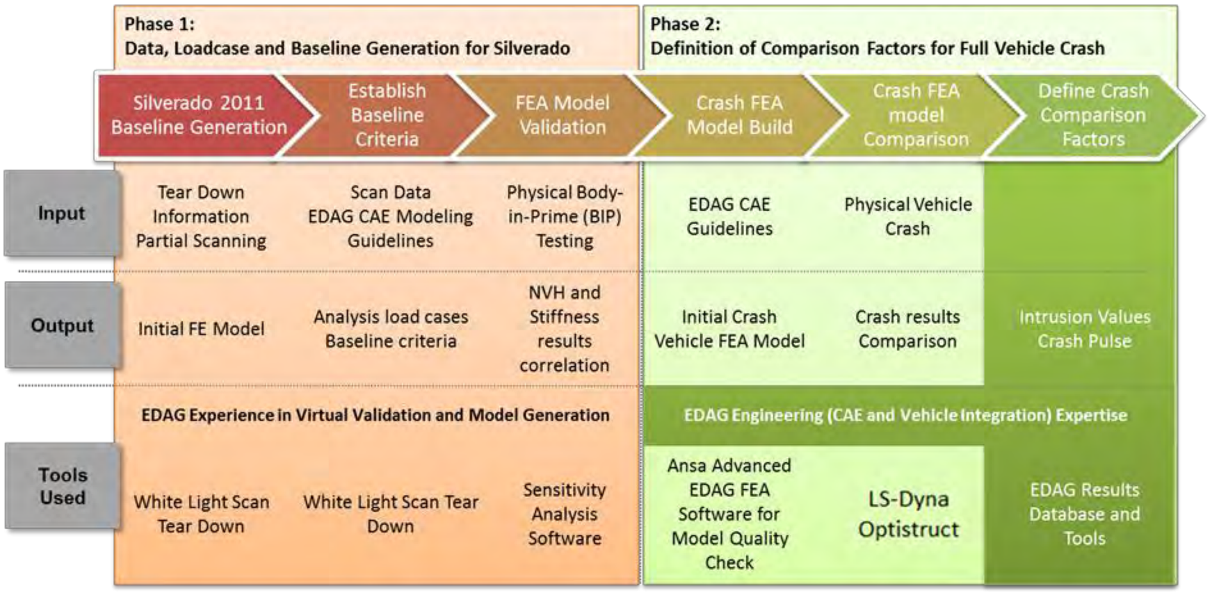



**Figure 4.18-51: Crash Comparison Factors**

The baseline crash results of the FMVSS 208 flat frontal, FMVSS 214 MDB side impact, and FMVSS214 Pole side impact loadcases were obtained during the crash model correlation stage (see analysis in **Section 4.18.2.1.3: FMVSS 214—20 5th Percentile Pole Side Impact**). The correlated crash model became the baseline crash model for the remaining loadcases. By using the correlated baseline model, the remaining four crash loadcases (listed below and analyzed in the following sections) were simulated to obtain the baseline performance results.

1) IIHS—40 mph, ODB Frontal Crash
2) IIHS—31 mph, MDB Side Impact
3) FMVSS 301—50 mph, MDB Rear Impact
4) Roof-Crush (utilizing IIHS roof-crush criteria)

#### 4.18.3.1 IIHS—40 mph ODB Frontal Crash

**Model Setup**

The model was setup in line with the IIHS moderate offset crash protocol (40% offset into a deformable barrier at 40 mph). The frontal impact model setup with ODB is shown in **Figure 4.18-52**.

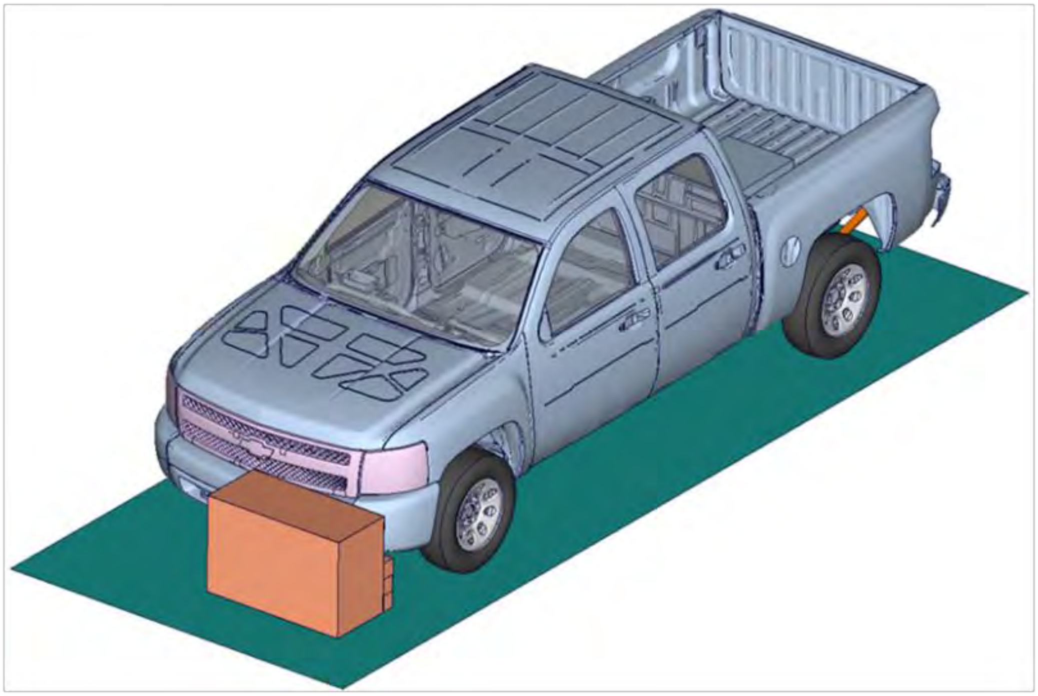


**Figure 4.18-52: IIHS ODB Frontal Crash Baseline Model Setup**

To measure passenger compartment structure integrity, data analysis points as shown in **Figure 4.18-53** were measured using the IIHS measurement protocol.

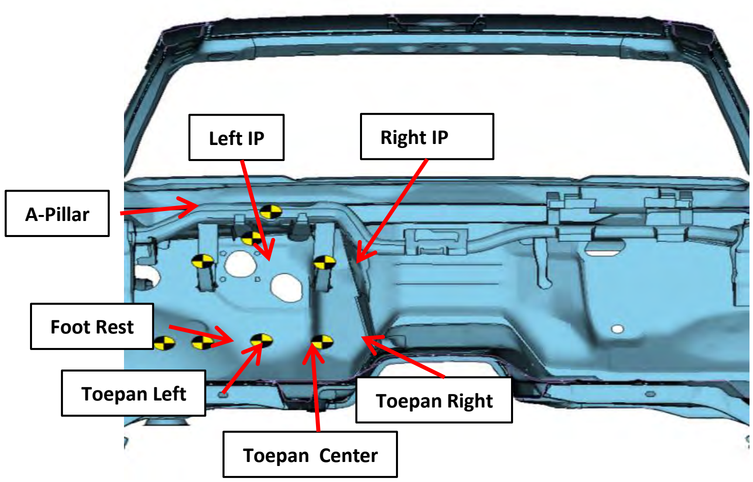



**Figure 4.18-53: Intrusion Measurement Locations**

The LS-DYNA simulation was carried out for a 150ms analysis time frame (the intrusion values reported are taken at end time state).

## Deformation Mode

The post-crash vehicle deformation modes of the CAE simulation are shown in **Figure 4.18-54** through **Figure 4.18-58**.

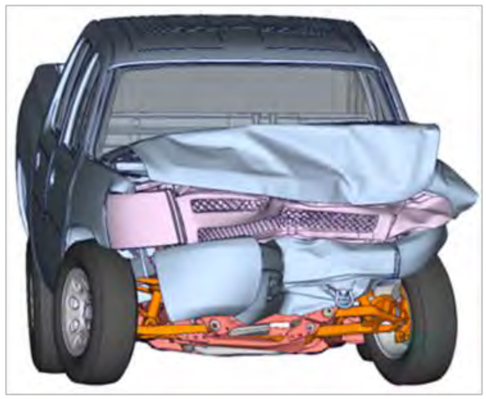


**Figure 4.18-54: IIHS Frontal Baseline Deformation Mode - Front View**

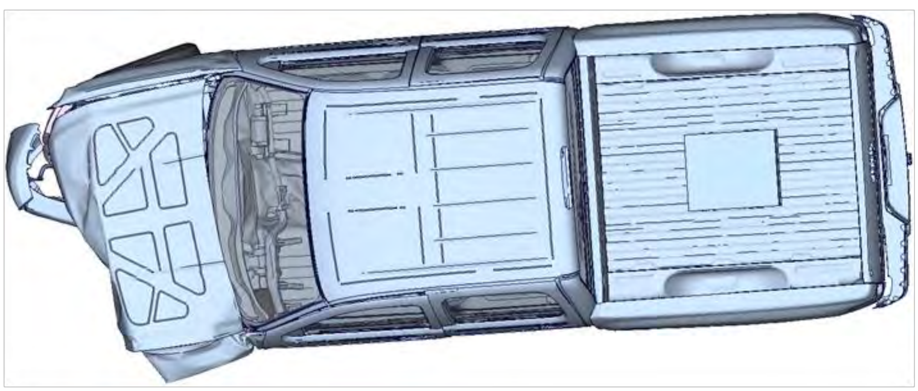


**Figure 4.18-55: IIHS Frontal Baseline Deformation Mode - Top View**

**Figure 4.18-56: IIHS Frontal Baseline Deformation Mode - Isometric View**

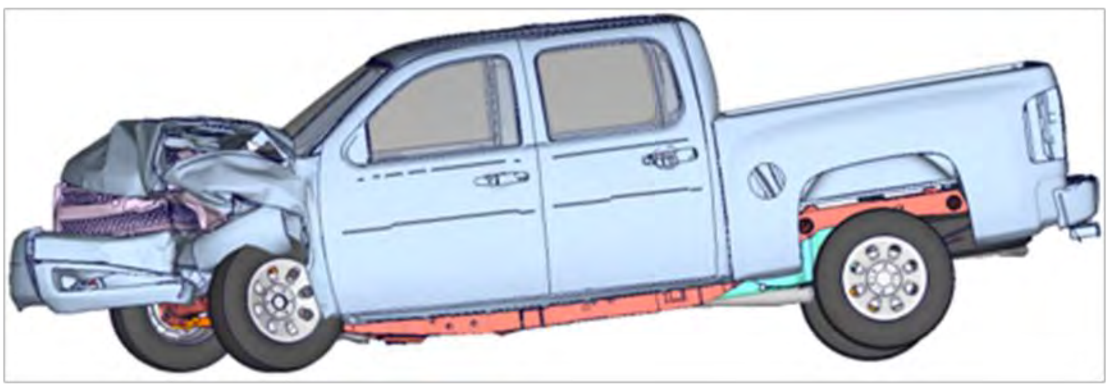


**Figure 4.18-57: IIHS Frontal Baseline Deformation Mode - Left Side View**

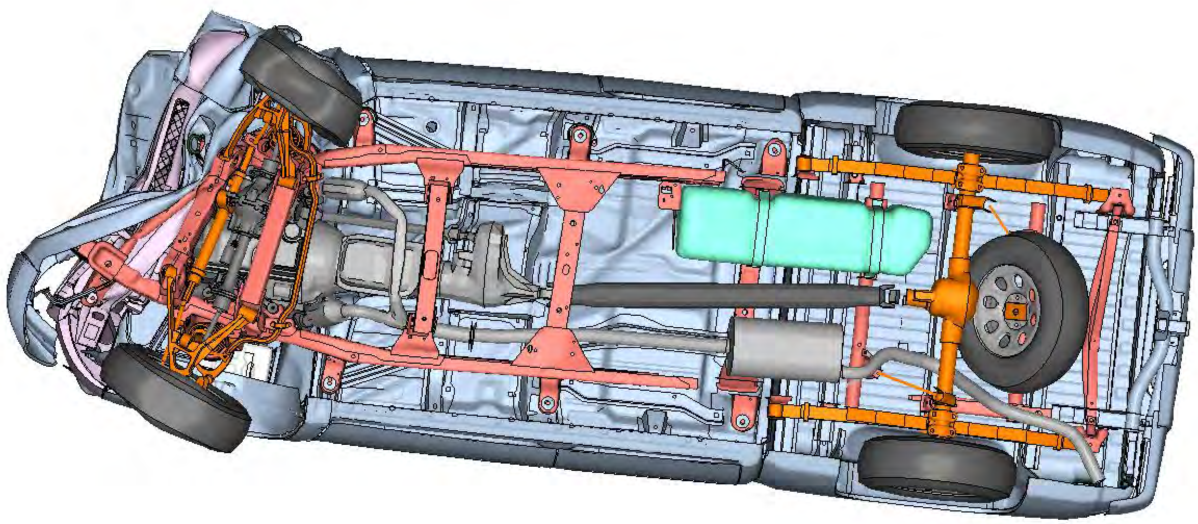


Figure 4.18-58: IIHS Frontal Baseline Deformation Mode - Bottom View

## Body Pulse, Dynamic Crush, and Intrusion

The vehicle velocity was measured in the x-direction at left and right side of the rear seat cross members and differentiated to obtain the vehicle acceleration in terms of crash pulse (in G's). The left-hand acceleration was used for the vehicle crash pulse. The vehicle crash acceleration pulse is shown in **Figure 4.18-59**.

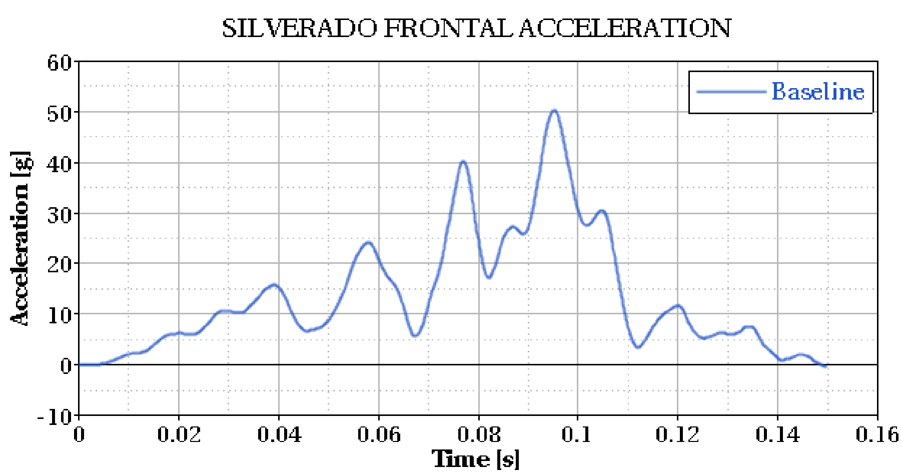



Figure 4.18-59: IIHS Frontal Baseline Vehicle Pulse

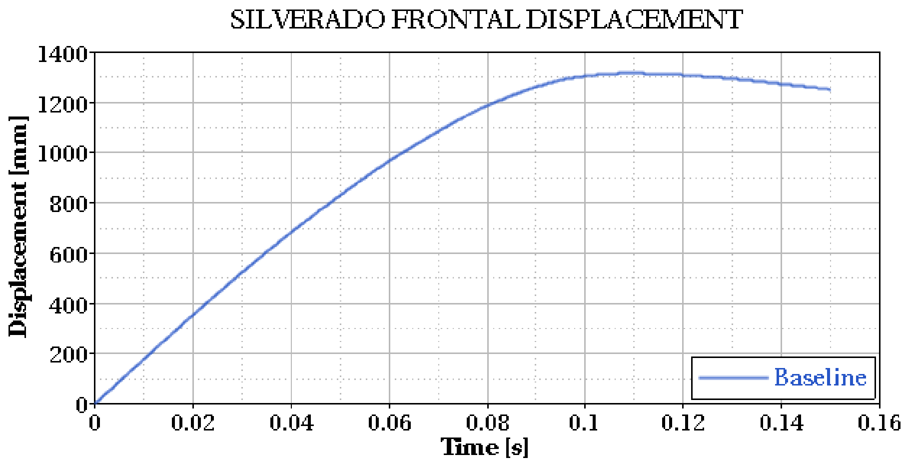



**Figure 4.18-60: IIHS Frontal Baseline Dynamic Crush with Barrier Deformation**

The structural performance (in terms of intrusions) is presented in **Figure 4.18-61** and **Table 4.18-11** as per the IIHS measurement protocols.

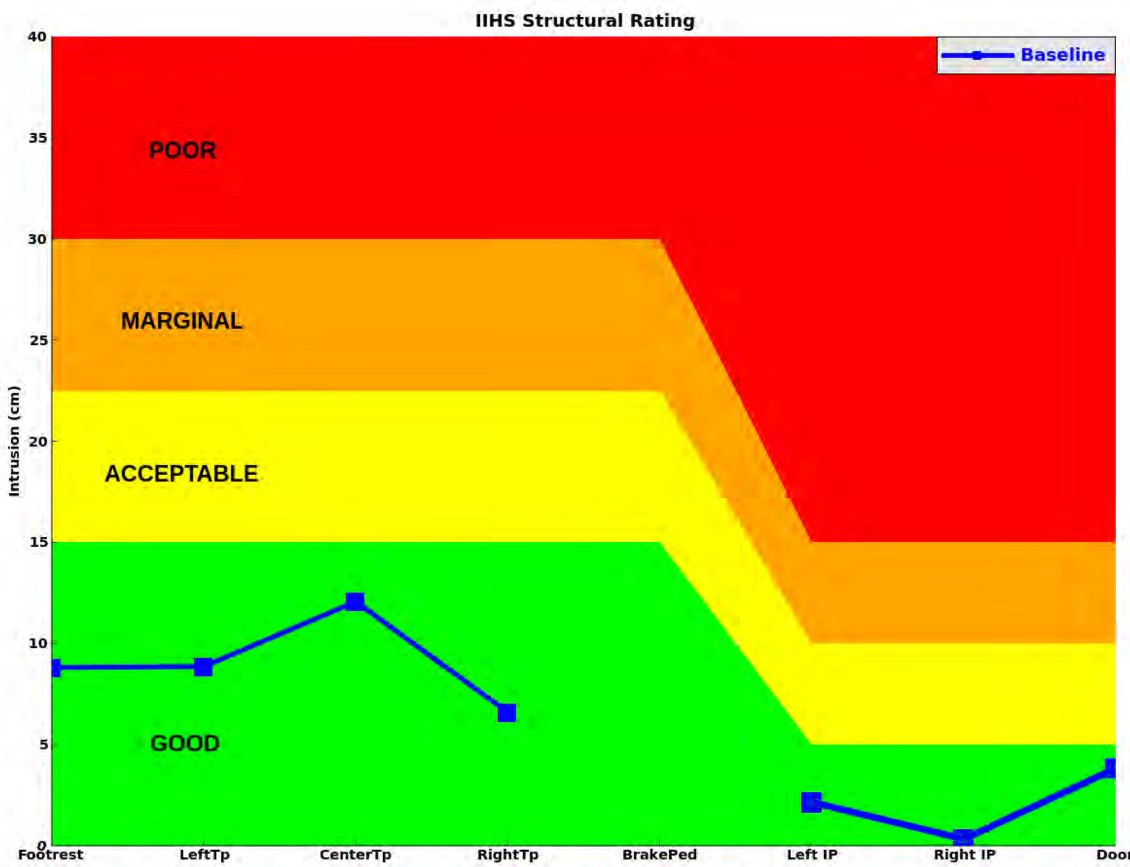



**Figure 4.18-61: IIHS Frontal Dash Panel Intrusion Plot**

A summary of the performance indicators of the baseline model for the offset frontal crash loadcase is listed in **Table 4.18-10** and **Table 4.18-11**.

**Table 4.18-10: IIHS Frontal Pulse and Dynamic Crush**

| No. | Frontal Crash Measurements | Silverado CAE Baseline |
|---|---|---|
| 1 | Pulse (g) | Average |
| | 1st Peak / Highest Peak | 6.23/50.3 |
| 2 | Time To Zero Velocity (ms) | 110.0 |
| 3 | Dynamic Crush Max. (mm) | 1317.2 |

**Table 4.18-11: IIHS Frontal Compartment Dash Intrusion**

| No. | Intrusion | Baseline (mm) |
|---|---|---|
| 1 | Driver Footrest | 88.1 |
| 2 | Driver Toe Pan Left | 88.6 |
| 3 | Driver Toe Pan Center | 120.7 |
| 4 | Driver Toe Pan Right | 66.0 |
| 6 | Left IP | 21.6 |
| 7 | Right IP | 3.3 |
| 8 | Door Aperture | 38.3 |

Based on the analysis of the deformation mode, dynamic crush, and compartment intrusions, this model was established as the EDAG targets for further frontal offset loadcase iterations.

#### 4.18.3.2 IIHS - 31mph, MDB Side Impact

### Model Setup

The model was setup in line with the IIHS side crash protocol (1500 kg Moving deformable barrier at 50 km/h)). The side impact model setup with the positioned MDB is shown in **Figure 4.18-62**.

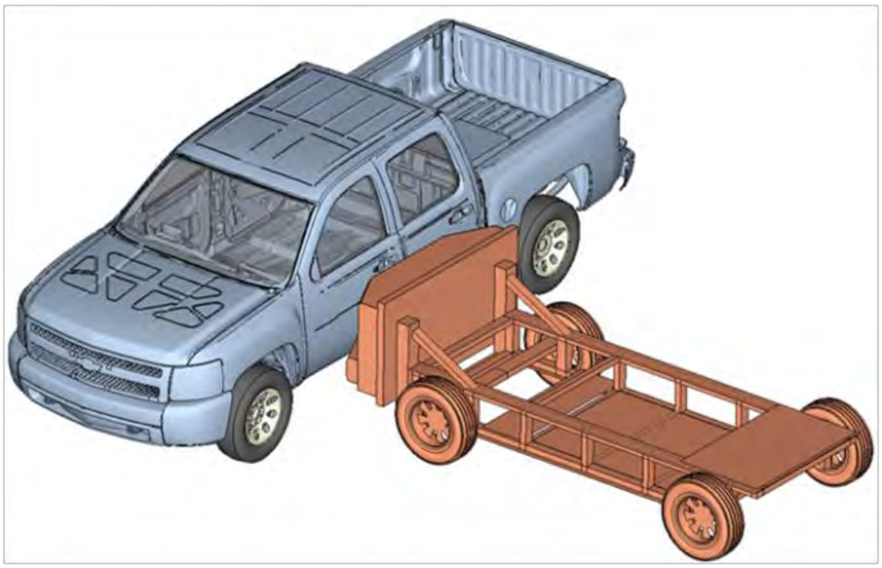


**Figure 4.18-62: IIHS MDB Side Impact CAE Model Setup**

The LS-DYNA simulation was carried out for a 200ms analysis time frame.

### Deformation Mode

As per the baseline model requirements, side-structure deformation and vehicle crash behaviors were analyzed. **Figure 4.18-63** and **Figure 4.18-64** show the pre and post-crash conditions. **Figure 4.18-64** shows the deformation mode at 200 ms (end of crash).

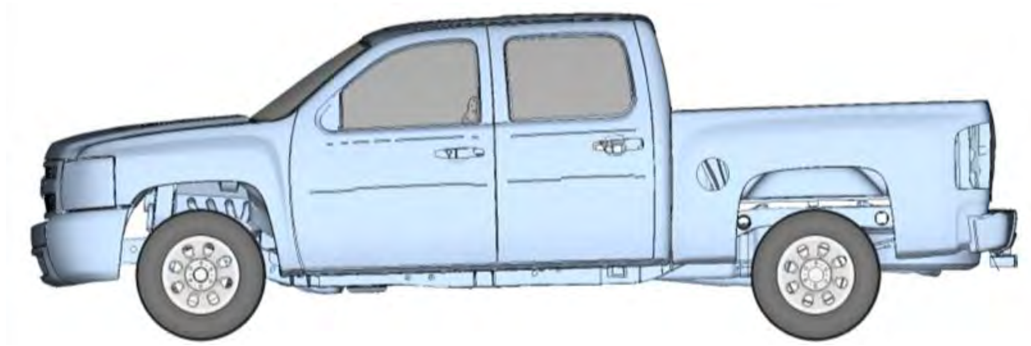


**Figure 4.18-63: IIHS Side Impact - Pre-Crash**

**Figure 4.18-64: IIHS Side Impact - Post-Crash**

**Figure 4.18-65** shows the door deformation modes at front door and rear door rear edges at 200ms (end of crash).

**Figure 4.18-65: IIHS Side Impact - Post-Crash**

**B-Pillar Velocity**

The side impact characteristics of the IIHS loadcase was recorded for the B-Pillar movement to analyze the impact pattern on the major structure that was impacted directly by the barrier. For this purpose the velocity of the side structure was measured on B-Pillar at 920 mm from the ground as shown in **Figure 4.18-66**.

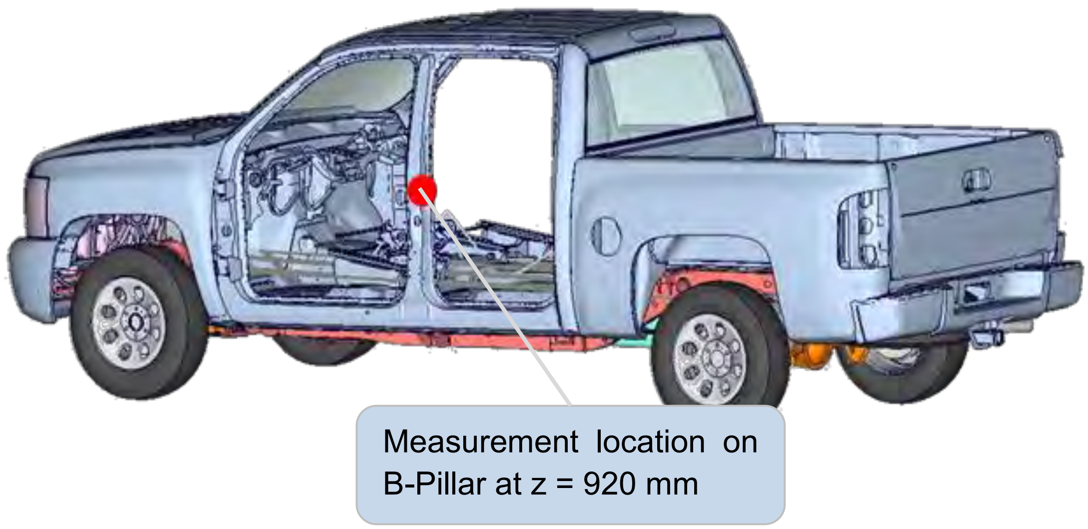



**Figure 4.18-66: B-Pillar Velocity Measurement Location**

The B-Pillar velocity is plotted for 200ms. **Figure 4.18-67** shows the side structure movement trend by B-Pillar velocity.


**Figure 4.18-67: B-Pillar Velocity**

## Structural Intrusion

The IIHS side protocol defines the measurement of the intrusion relative to a plane at the seat centerline. A single intrusion value is reported for the two tests conducted on the Silverado in the 2007-2013 timeframe as detailed below.

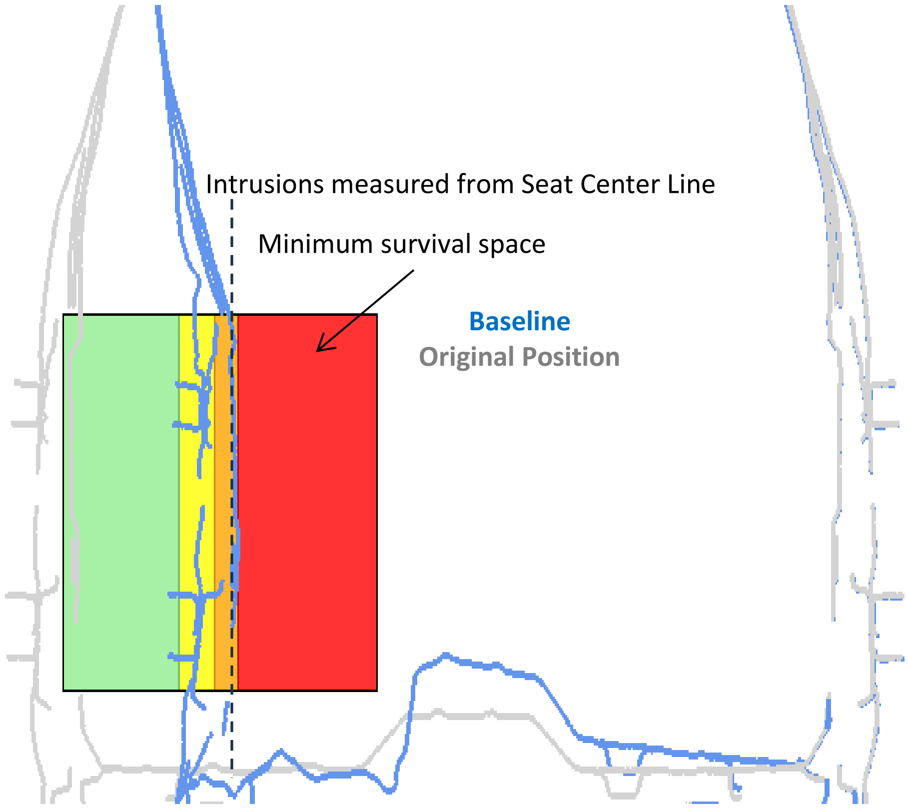



**Figure 4.18-68: IIHS Side Intrusion Zones**

**Table 4.18-12: Side Structure Intrusion with Survival Space Rating**

| Test | (cm) | Rating |
|---|---|---|
| CES0903 2007Silverado | +35.0 | Poor |
| CES09212010Silverado | -50.0 | Acceptable |
| CAE Baseline | -0.1 | Marginal |

The test results show an improvement in performance from 2007 to 2010 with the changes implemented in the body structure during that period.

In addition to the IIHS intrusion measurement the intrusion profile (in Z) of the B-Pillar and the side structure (in X) are monitored as detailed in **Figure 4.18-69** and **Figure 4.18-70**. The intrusions are detailed relative to the un-deformed side structure in **Table 4.18-13**.


Figure 4.18-69: Side Structure Deformations

Table 4.18-13: Relative Intrusions

| Measured Location | Baseline (mm) |
|---|---|
| Level-7 | 166 |
| Level-6 | 299 |
| Level-5 | 334 |
| Level-4 | 351 |
| Level-3 | 345 |
| Level-2 | 333 |
| Level-1 | 310 |

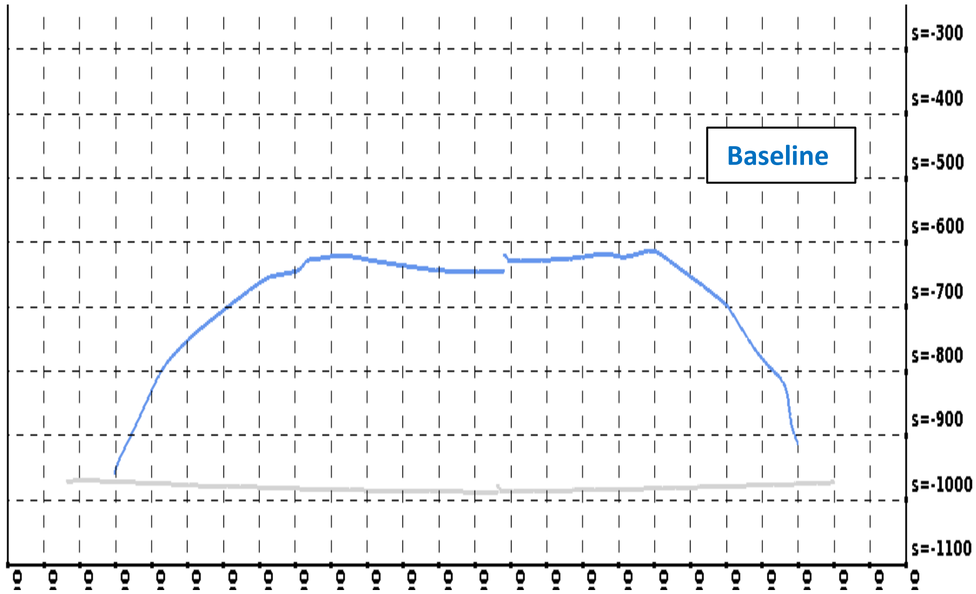



**Figure 4.18-70: Side Structure Exterior Crush**

### 4.18.3.3 FMVSS 301—50mph MDB Rear Impact

**Model Setup**

The model was setup in line with the FMVSS 301 side crash protocol (1,380kg MDB at 80km/h with a 70% overlap). The rear impact model setup with the positioned MDB is shown in **Figure 4.18-71**.

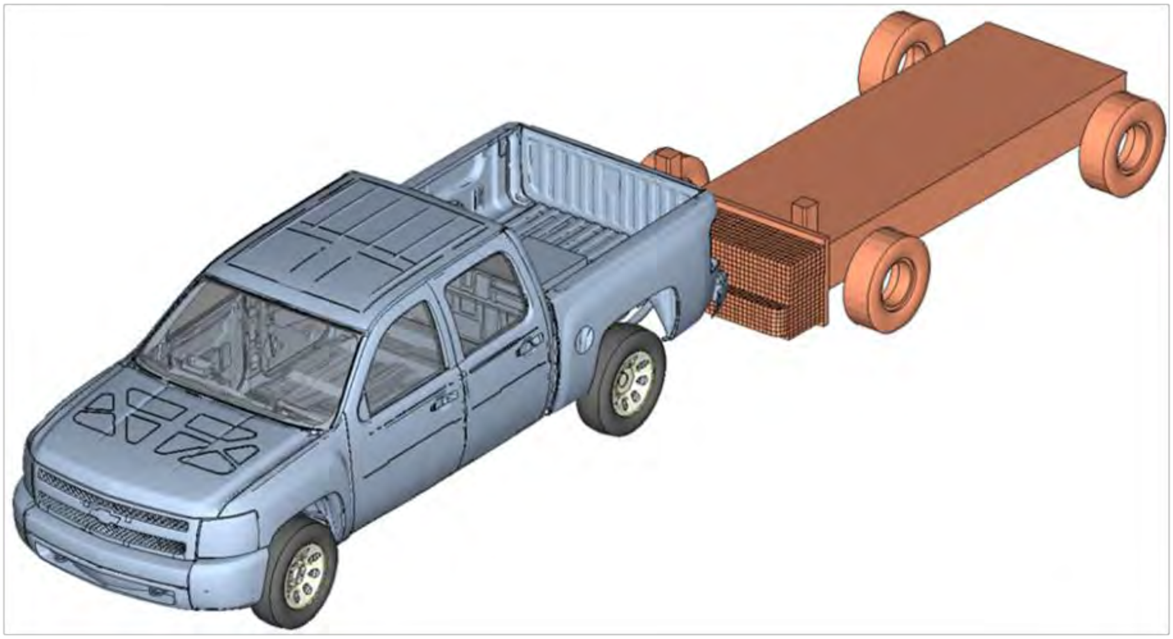


**Figure 4.18-71: Rear Impact Baseline Model Setup**

The LS-DYNA simulation was carried out for a 120ms analysis time frame. FMVSS 301 test results are not available for this selected Silverado vehicle configuration.

## Deformation Mode

The deformation modes of the rear-impact simulation are shown in **Figure 4.18-72** through **Figure 4.18-75**.

The model shows that the deformation in the regions around the fuel system is controlled with adequate protection for the tank and fuel filler.

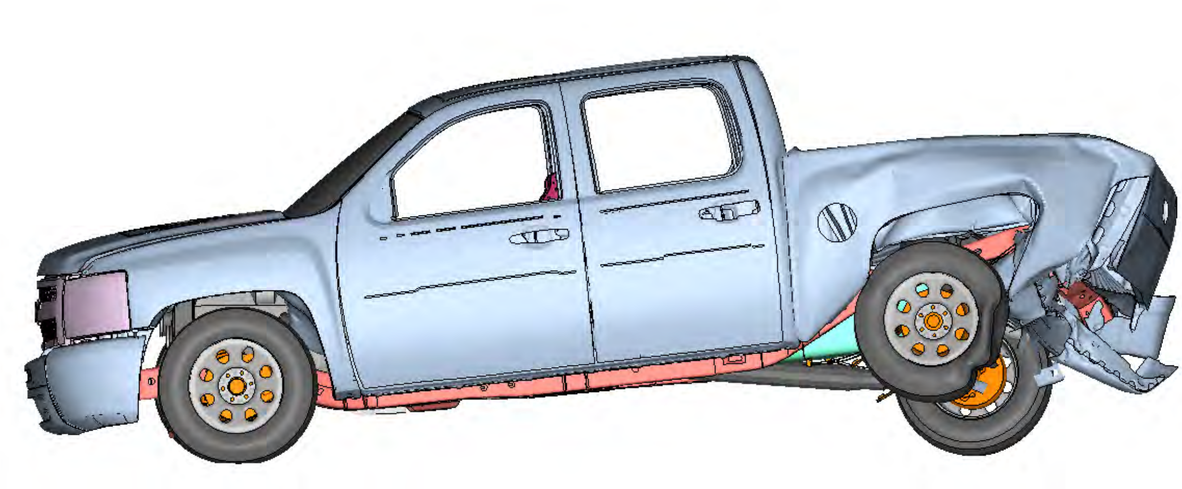


**Figure 4.18-72: Deformation Mode - Left Side View**

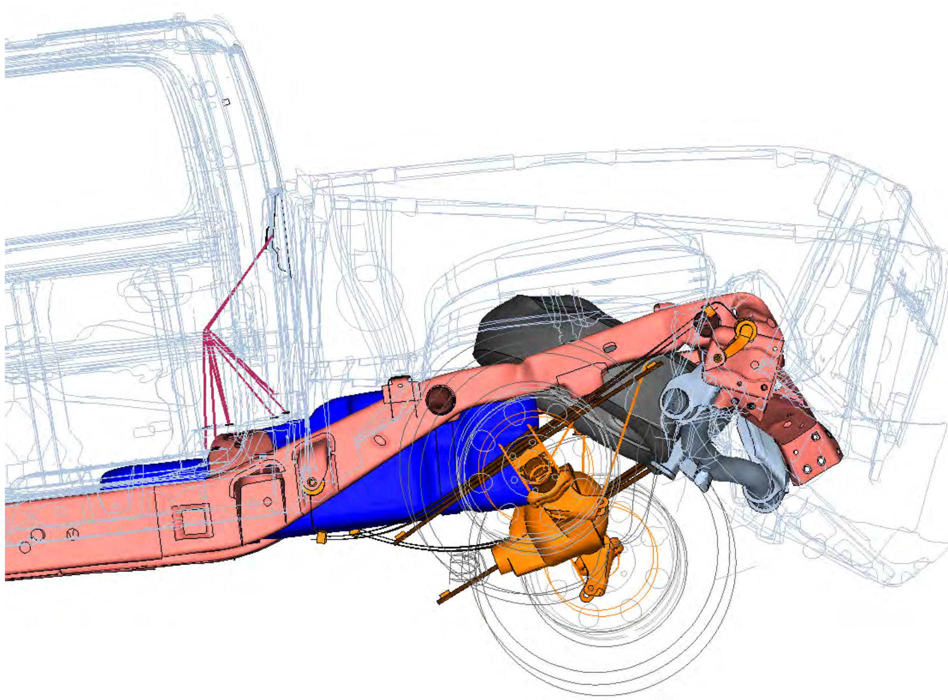


**Figure 4.18-73: Deformation Mode of Rear Underbody Structure - Left Side View at 120ms**

The bottom view of the rear underbody structure around the fuel tank area at the end of the crash (120ms) is shown in **Figure 4.18-74** and **Figure 4.18-75**.

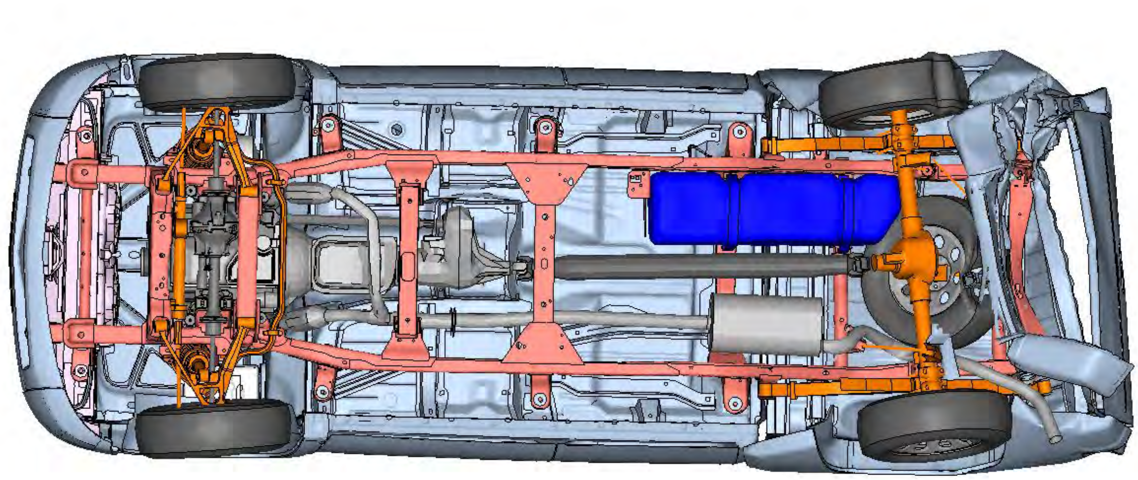


**Figure 4.18-74: Deformation Mode - Bottom View at120ms**

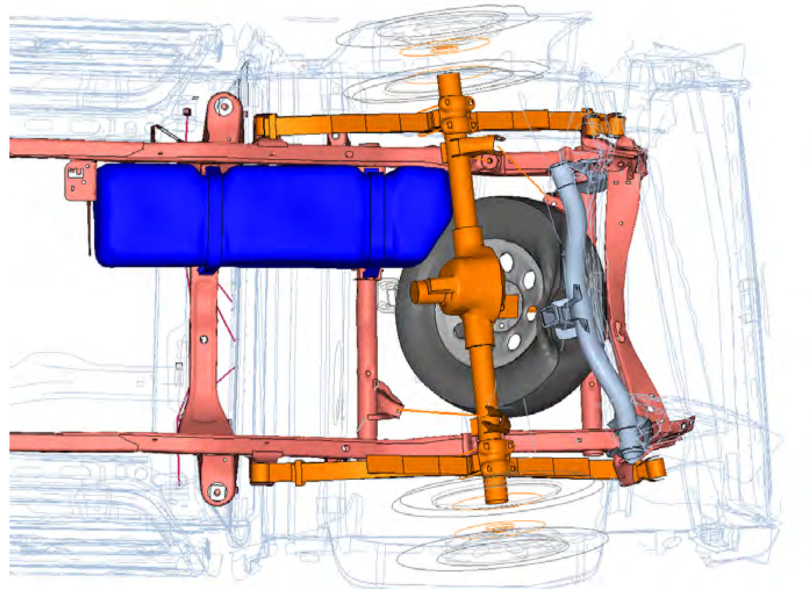


**Figure 4.18-75: Deformation Mode of Rear Underbody Structure - Bottom View at 120ms**

## Fuel Tank Deformation

**Figure 4.18-76** shows the plastic strain distribution on the fuel tank system at the end of the crash. It indicates no significant risk of fuel system damage as the maximum strain is less than 10%, which is less than the expected plastic strain required to fail the tank material.

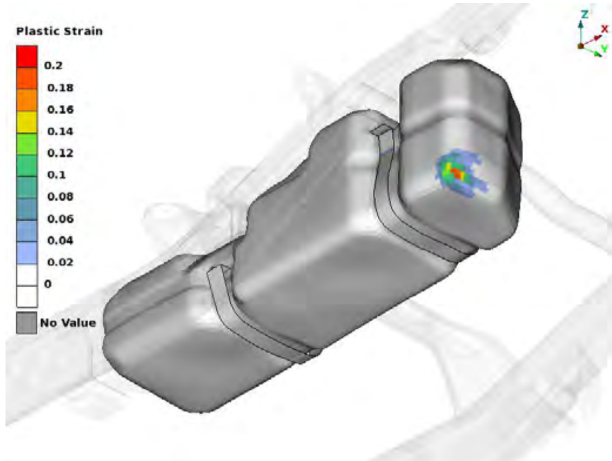



**Figure 4.18-76: Fuel Tank Plastic Strain Plot of Baseline**

## Structural Deformation

The structural performance is monitored by deformation metrics in several zones as detailed in **Figure 4.18-77**. Zones 1 to 4 are measured on the underbody with two further measurements to monitor the deformation of the rear door aperture.

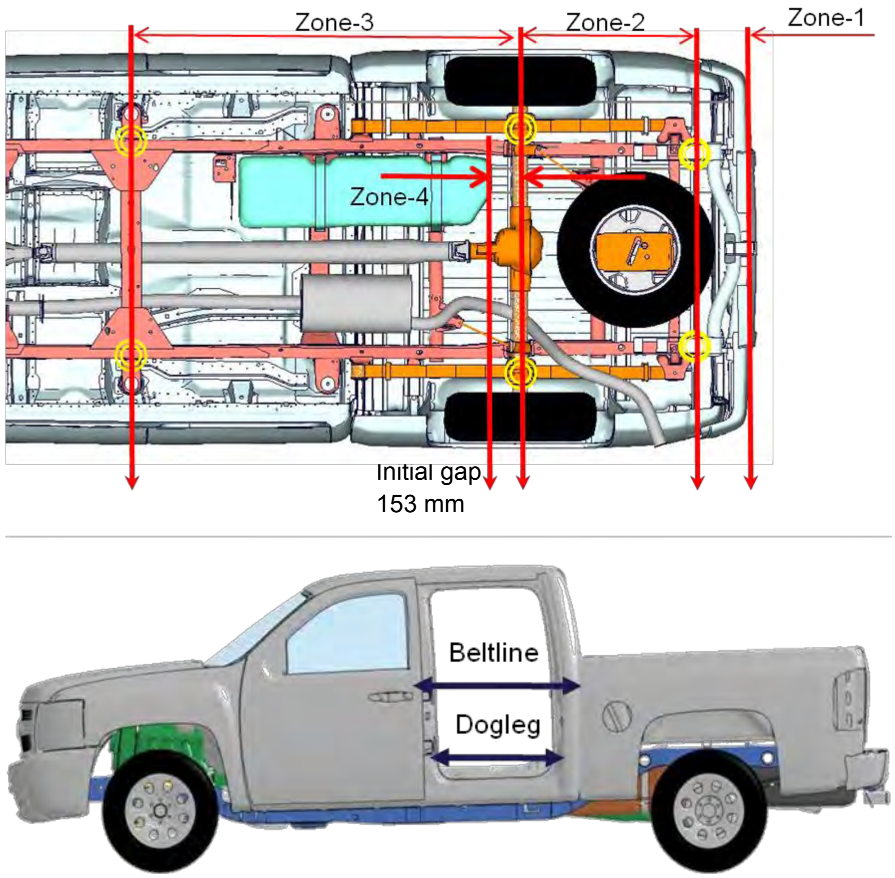



**Figure 4.18-77: Rear Impact, Structural Deformation Measurement Area**

The rear impact deformation measurements of the baseline model are summarized in **Table 4.18-14**.

**Table 4.18-14: Rear Impact Structural Performance**

| Model | Under Structure Zone Deformation (mm) | | | | Door Opening (mm) | |
|---|---|---|---|---|---|---|
| | Zone-1 | Zone-2 | Zone-3 | Zone-4 (Max.) | Beltline | Dogleg |
| Baseline | 402.8 | 348.7 | 132.1 | 115.2 | 2.6 | -1.8 |

#### 4.18.3.4 FMVSS 216a—Roof Crush Resistance

**Model Setup**

The IIHS and FMVSS 216a roof crush resistance test determines strength of the roof structure when loaded by a rigid platen under static loading as shown in **Figure 4.18-78**. The test model is loaded and assessed as per the IIHS protocol (the largest main differences being the loading on a single side and no internal measurement of the occupant space reduction).

The platen is displaced in a quasi-static analysis to achieve the required 5" of displacement and the platen force monitored. The rating criteria for the IIHS protocol are shown in **Table 4.18-15**.

**Table 4.18-15: Rear Impact Structural Performance**

| Roof Strength Rating Boundaries | |
|---|---|
| SWR | Rating |
| ≥ 4.00 | Good |
| ≥ 3.25 to < 4.00 | Acceptable |
| ≥ 2.50 to < 3.25 | Marginal |
| < 2.50 | Poor |

A basic failure model was implemented for the glass to prevent unrealistic loading in the roof crush (no data was available for the calibration of the material model). See recommendations in **Section 7.2.6**.

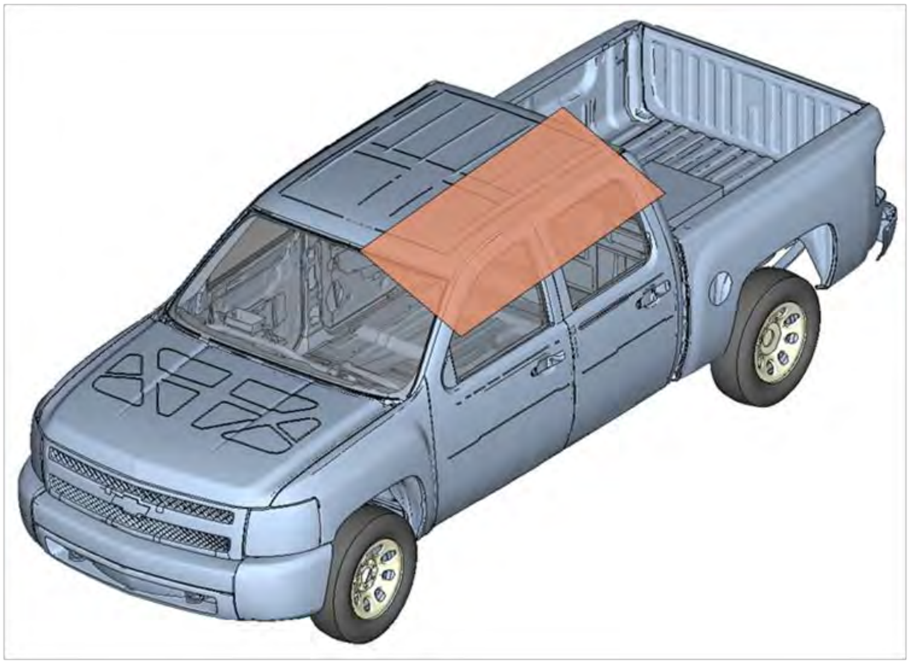


**Figure 4.18-78: Roof Crush Baseline Model Setup**

## Deformation Mode

The roof crush deformation mode at 100ms after crush event is shown in **Figure 4.18-79** through **Figure 4.18-83**.

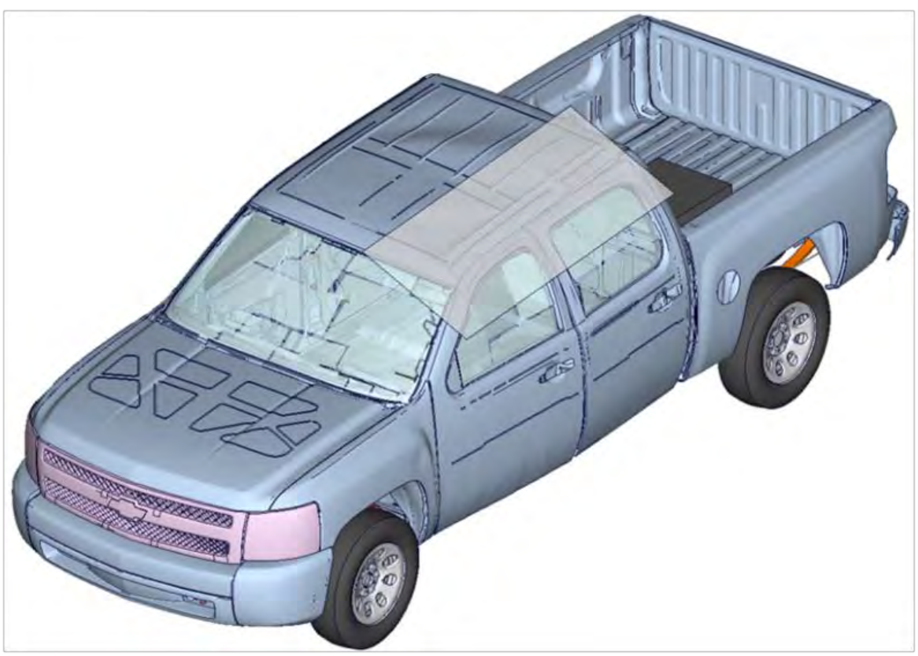


**Figure 4.18-79: Roof Crush Baseline after Crush View**

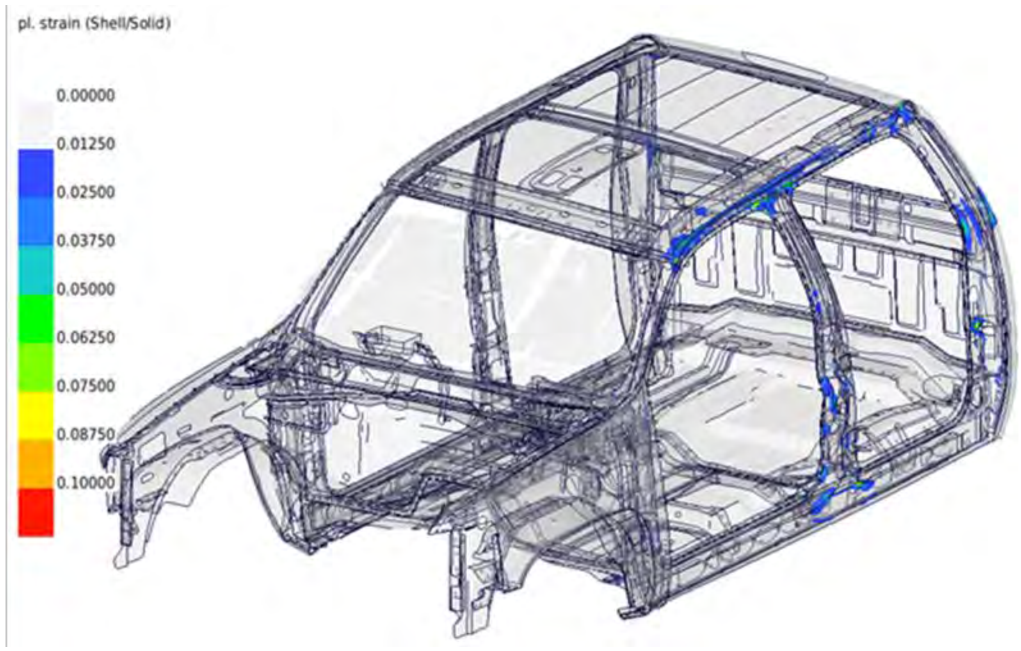



**Figure 4.18-80: Roof Crush Plastic Strain Areas ISO View at 100ms**

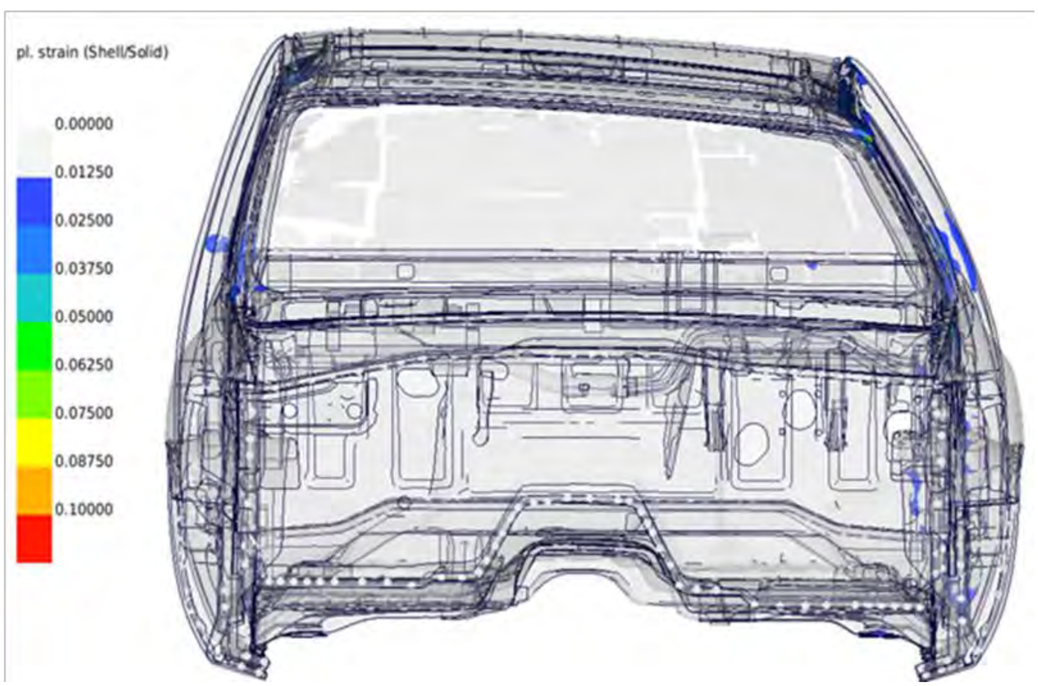



**Figure 4.18-81: Roof Crush Plastic Strain Areas Front View at 100ms**

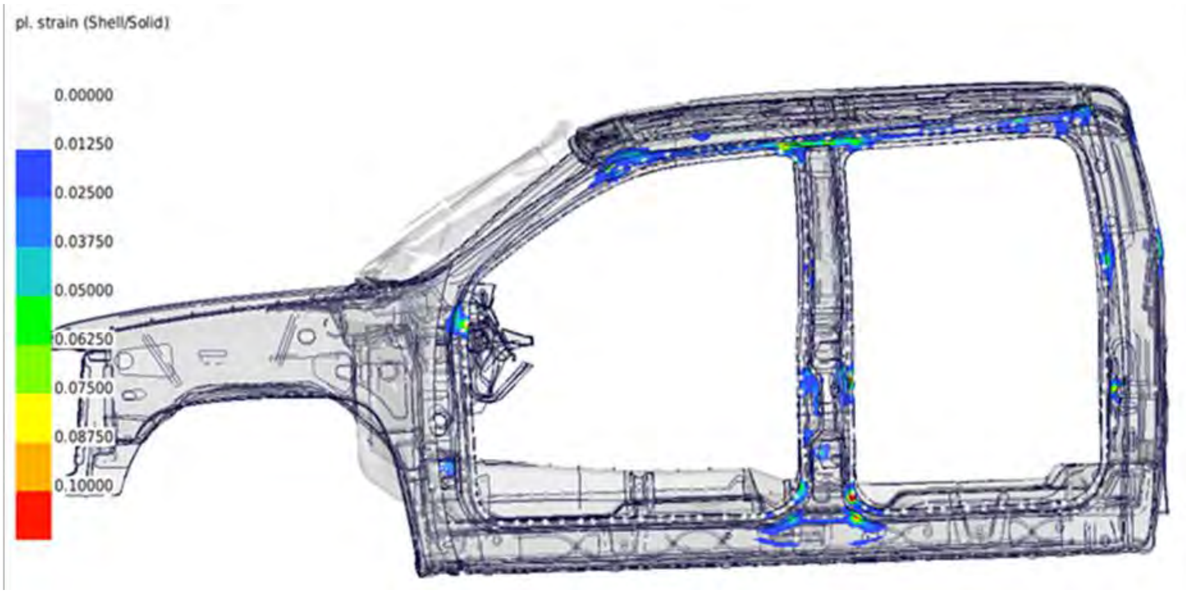



**Figure 4.18-82: Roof Crush Plastic Strain Areas Side View at 100ms**

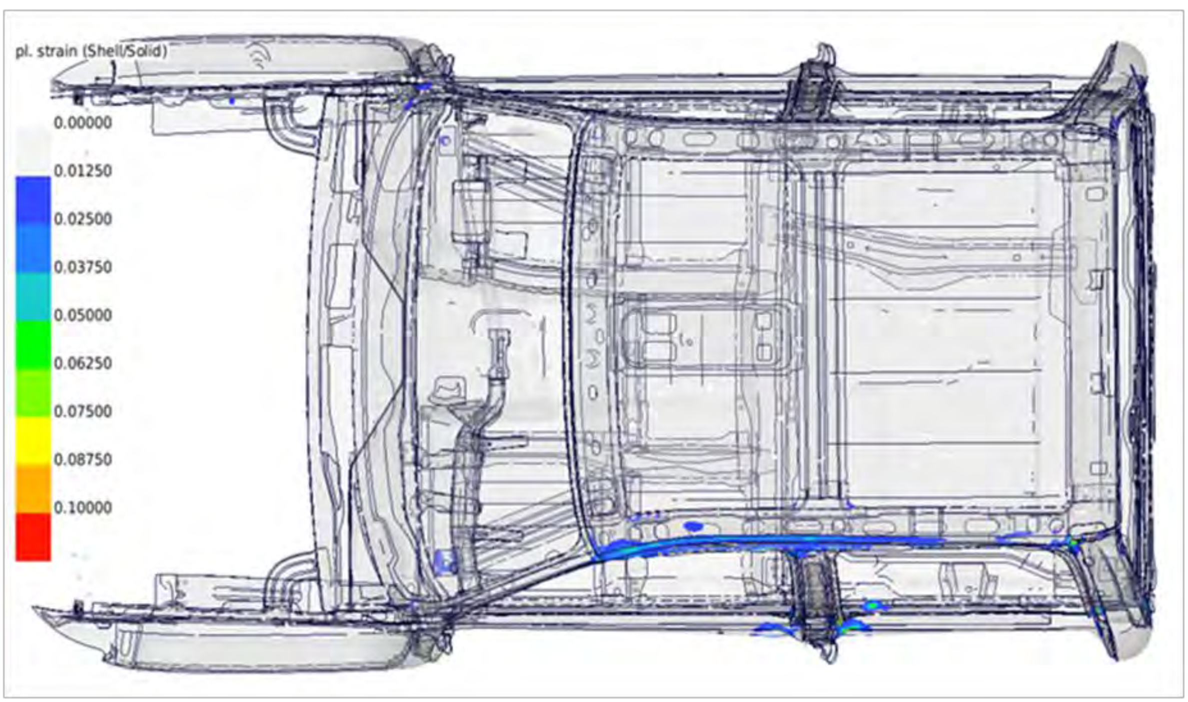



**Figure 4.18-83: Roof Crush Plastic Strain Areas Top View at 100ms**

The ultimate performance of roof crush resistance was determined by the platen force level over the vehicle roof structure. The force versus displacement curve of the platen is illustrated in **Figure 4.18-84** with the roof strength-to-weight ratio shown in **Figure 4.18-85**.

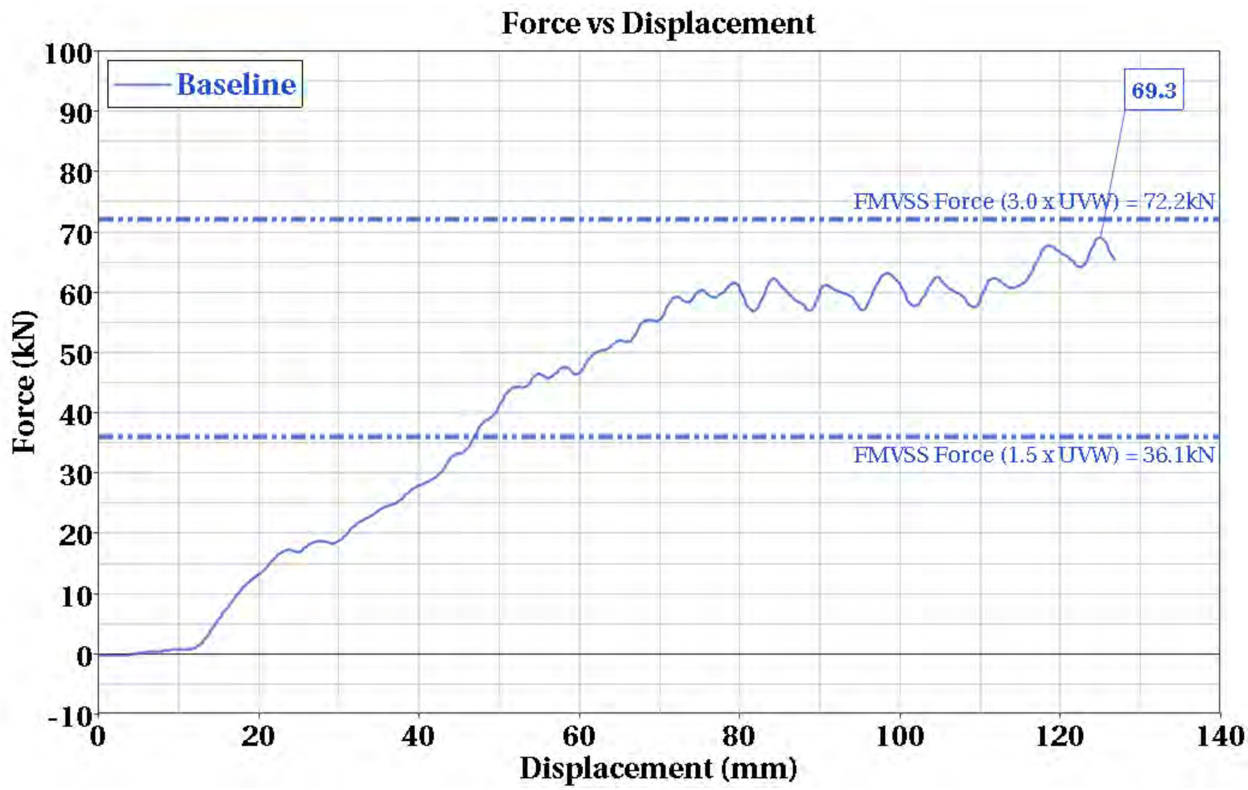



**Figure 4.18-84: Roof Crush Force vs. Displacement Plot of Baseline**

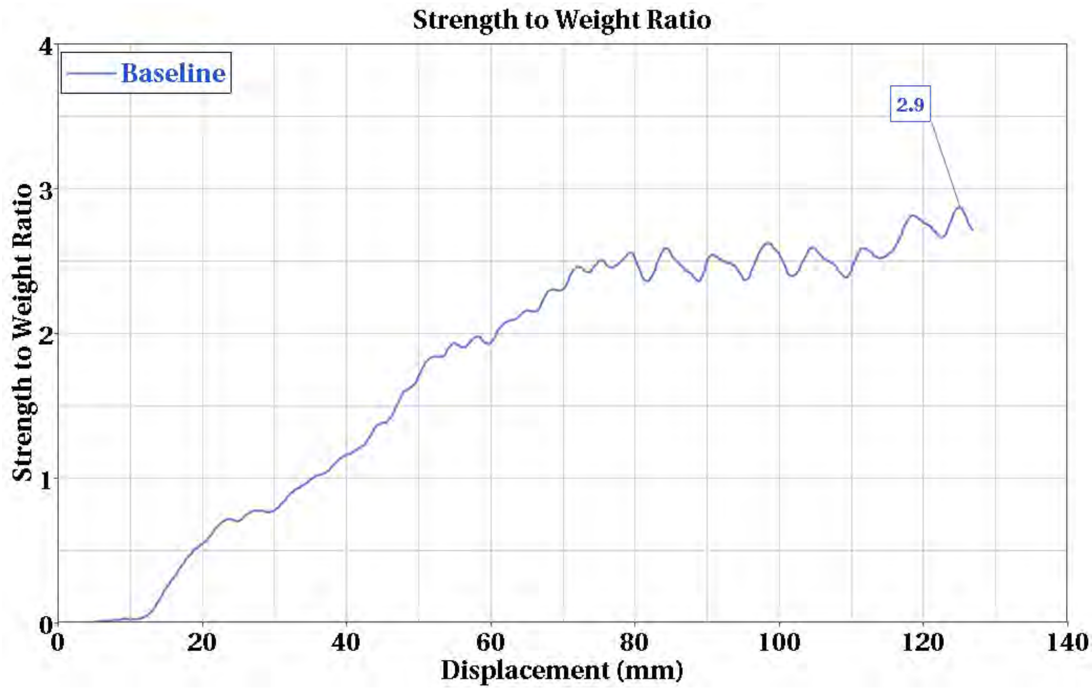



**Figure 4.18-85: Roof Strength to Weight Ratio**

**Table 4.18-16: Roof Strength Summary of Baseline Model**

| Model | Curb Wt. (kg) | Peak Force (KN) | Strength to weight Ratio | IIHS Rating |
|---|---|---|---|---|
| Baseline | 2,454 | 69.3 | 2.9 | Marginal |
| IIHS Test (2011) | 2,341 | 71.8 | 3.13 | Marginal |

**Summary of Model Performance**

The model performance is compared against the IIHS test performed on a 2011 Silverado in **Table 4.18-16**. The results show a "marginal" rating for the structure in both cases.

### 4.18.4 Modularization and System Analysis Results

In Phase 3 the final data set is constructed for use in the mass reduction optimization process. As part of the System Analysis and Definition Systems Comparison Factors tasks **(Figure 4.18-86)**, body closure acceptance criteria are established.

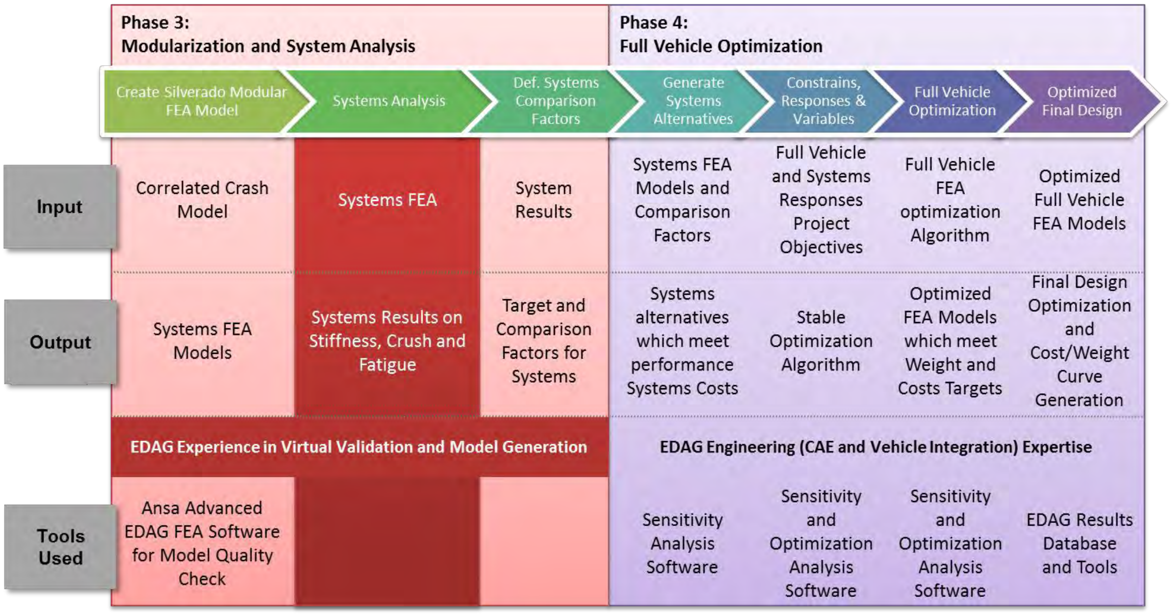



**Figure 4.18-86: Phase Three Task Summary**

### 4.18.4.1 System Results and Definition of System Comparison Factors

The following section addresses the methodology for establishing the baseline closure performance attributes. Based on EDAG's experience for closures of a similar size and construction, along with the baseline values established in this analysis, closure targets where established. The target values are used in the mass reduction phase of the analysis to ensure closure mass reduction ideas do not result in performance degradation.

#### 4.18.4.1.1 <u>Baseline Front Door</u>

The following loadcases were considered to analyze the front door strength.

1) Frame Lateral Rigidity (Front)
2) Frame Lateral Rigidity (Rear)
3) Beltline Strength - Compression
4) Beltline Strength - Expansive
5) Torsional Rigidity
6) Door Sag
7) Oil Canning Load Deflection

The FEA model of the front door was developed in ABAQUS non-linear solver format. The gauge and material grade maps of the front door are provided in **Figure 4.18-87** and **Figure 4.18-88**.

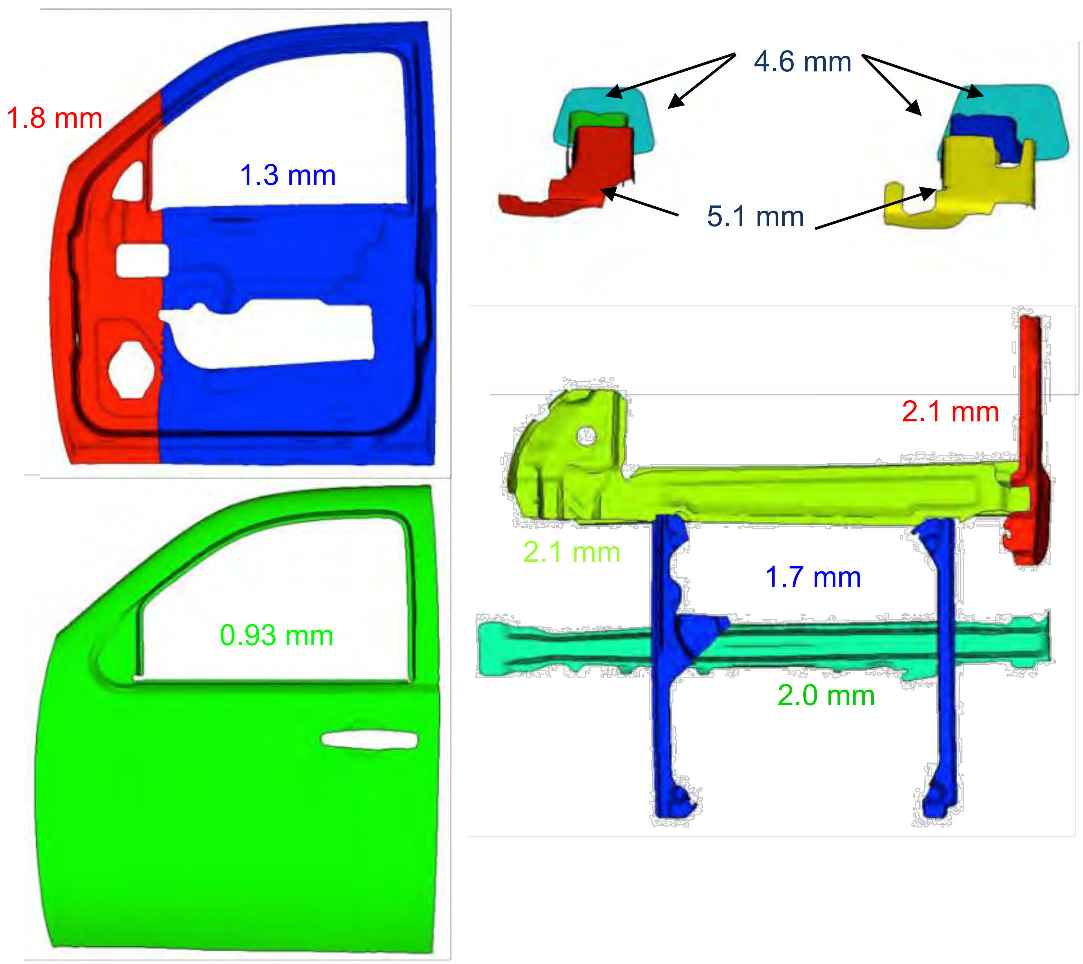



**Figure 4.18-87: Gauge Map of Front Door**


**Figure 4.18-88: Material Grade Map of Front Door**

Taking the vehicle symmetry into consideration, only the left hand (LH) side front door FEA model was developed and the results of the right hand (RH) side front door were assumed to be same that of LH side. The FEA model was constrained and loaded as per the loadcase requirements. The necessary boundary conditions and loading conditions for the above loadcases are shown in **Figure 4.18-89**.

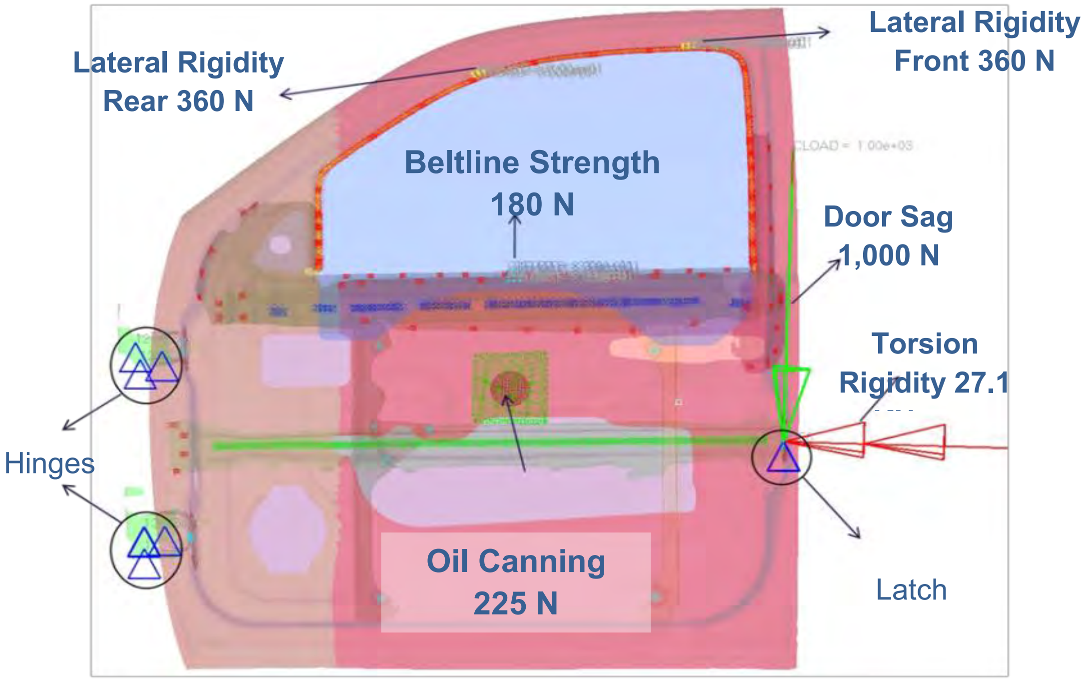



**Figure 4.18-89: Front Door Loading and Boundary Conditions**

Frame rigidity analysis was carried out for two loads. One by applying a static lateral load of 360 N at front and another by applying a static load of 360 N at rear side of the frame. The door was constrained rigidly at the hinges Degrees of Freedom (DOF 1-6) and latches (DOF 2, 3, 5, and 6) accordingly.

Beltline strength was calculated by simulating the static load of 180 N applied at the middle of the beltline. The compression characteristics were studied by applying the load towards the inboard direction of the vehicle and expansion characteristics were studied by applying the load towards the outboard direction of the vehicle. The door was constrained rigidly at the hinges (DOF 1-6) and latches (DOF 2, 3, 5, and 6) accordingly.

Torsional rigidity of the door was studied by applying a moment of 27.1 KN-mm at the latch point about the axis along door longitudinal direction. The door was constrained at the hinges (DOF 1-6) and latches (DOF 2, 3, 5, and 6) accordingly.

Door sag simulation was carried out by applying a downward vertical load of 1000 N at the latch point. The door was constrained rigidly at the hinges using DOF 1-6 and latch using DOF 2 only accordingly.

Oil canning load deflection is an important measure to study the door deformation due to external pressures such as palm impression, thumb load, denting. The oil canning simulation was carried out to obtain the allowable deflection. A rigid circular pad was created over the outer panel of the door. The rigid pad was allowed to move towards the door (inboard direction) by applying a load 225 N in the normal direction of the loading area as shown in **Figure 4.18-89**. The door was constrained at the hinges (DOF 1-6) and latches (DOF 2, 3, 5, and 6) accordingly.

The analysis results of the front door performance study are provided in **Table 4.18-17**.

**Table 4.18-17: Front Door Performance Results Baseline**

| No. | Loadcase | Target(mm) | Baseline Results(mm) |
|---|---|---|---|
| 1 | Frame Lateral Rigidity (Front) | <0.5 set | no set |
| 2 | Frame Lateral Rigidity (Rear) | <0.5 set | no set |
| 3 | Beltline Strength - Compression | <3.0 | 0.96 |
| 4 | Beltline Strength – Expansive | <3.0 | 0.94 |
| 5 | Torsional Rigidity | <4.0 | 2.98 |
| 6 | Door Sag | <2.0 set | 0.62 set |
| 7 | Oil Canning Load Deflection | <0.05 set | no set |

It is observed that, when compared to the generic door performance targets, the baseline front door shows no significant deflections due to the frame loading and oil canning. The baseline door deflections are within the acceptable range for the remaining loadcases. These performance measures are considered as baseline targets for the further iterations.

#### 4.18.4.1.2 Baseline Rear Door

In a similar approach, the FEA model was developed for rear door and performance analysis was carried for the same type of loadcases as the front door. The gauge and material grade maps of the rear door are provided in **Figure 4.18-90** through **Figure 4.18-92**.

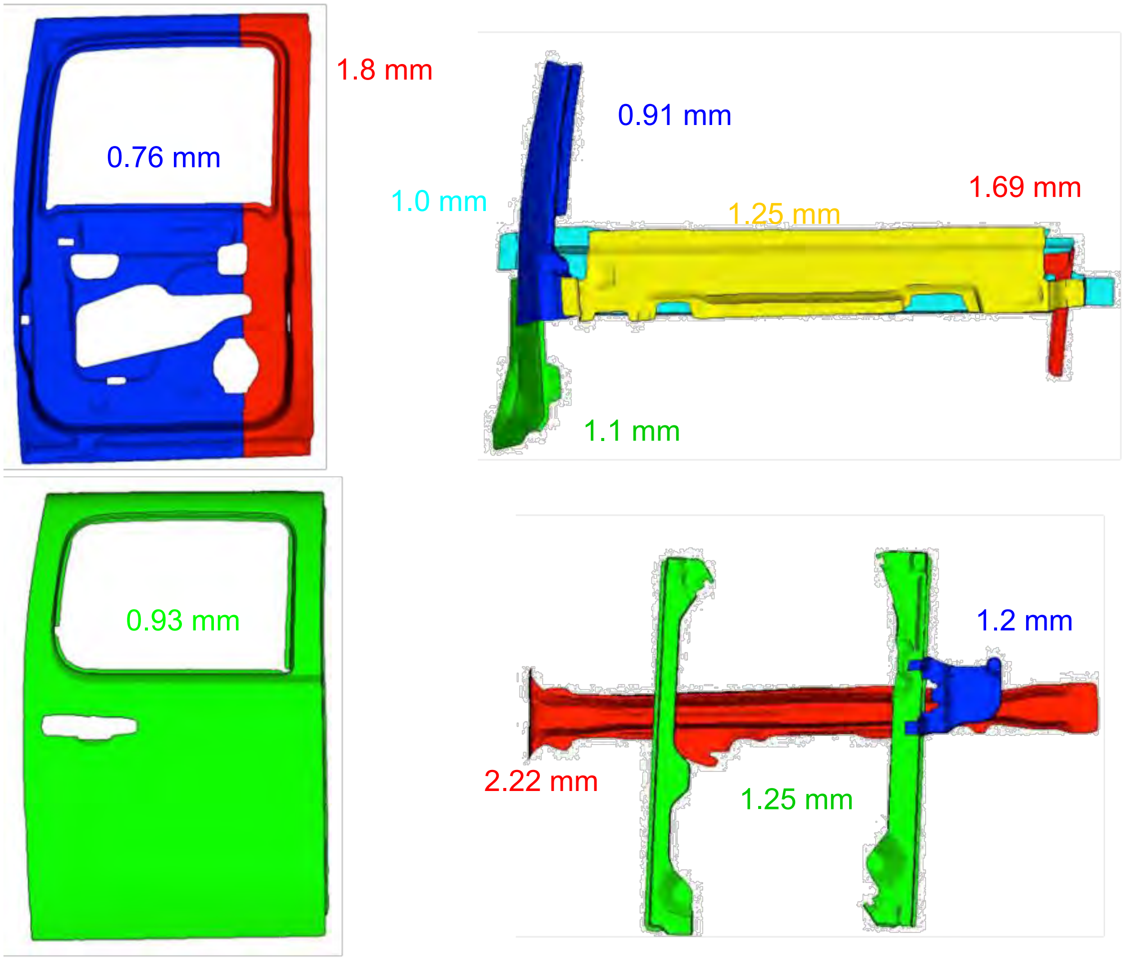



**Figure 4.18-90: Gauge Map of Rear Door**

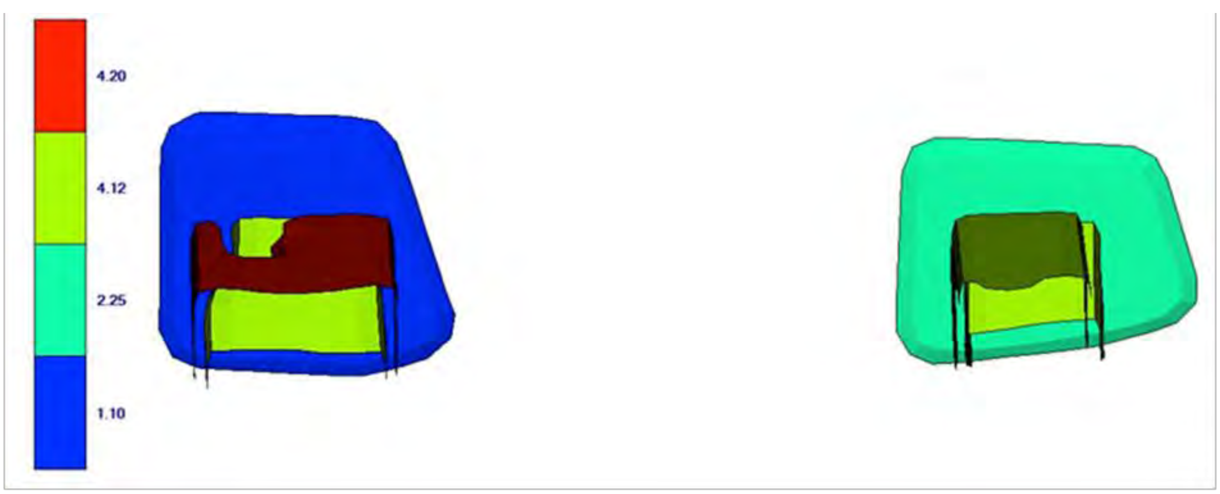



**Figure 4.18-91: Gauge Map of Rear Door Hinges**

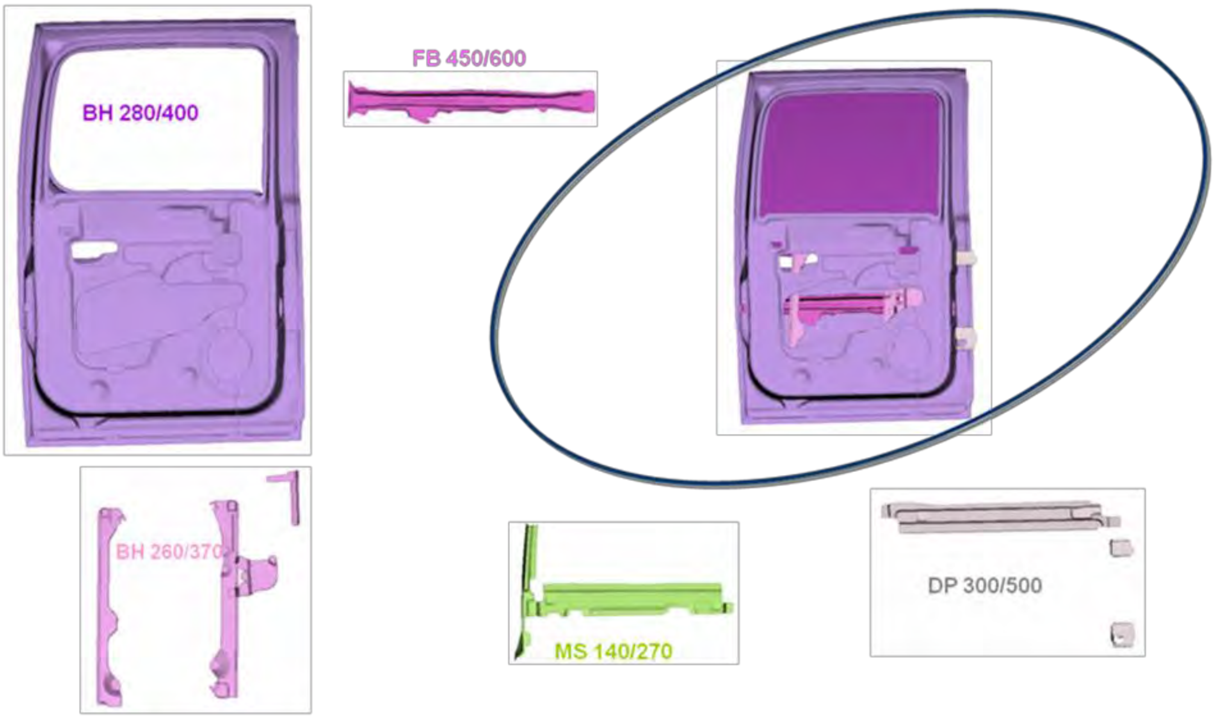



**Figure 4.18-92: Gauge Map of Rear Door**

Taking the vehicle symmetry into consideration, only the left hand (LH) side rear door FEA model was developed and the results of the right hand (RH) side rear door were assumed to be same as the LH side. The FEA model was constrained and loaded as per the loadcase requirements. The necessary boundary conditions and loading conditions for the same type of rear door loadcases are shown in the following **Figure 4.18-93**.

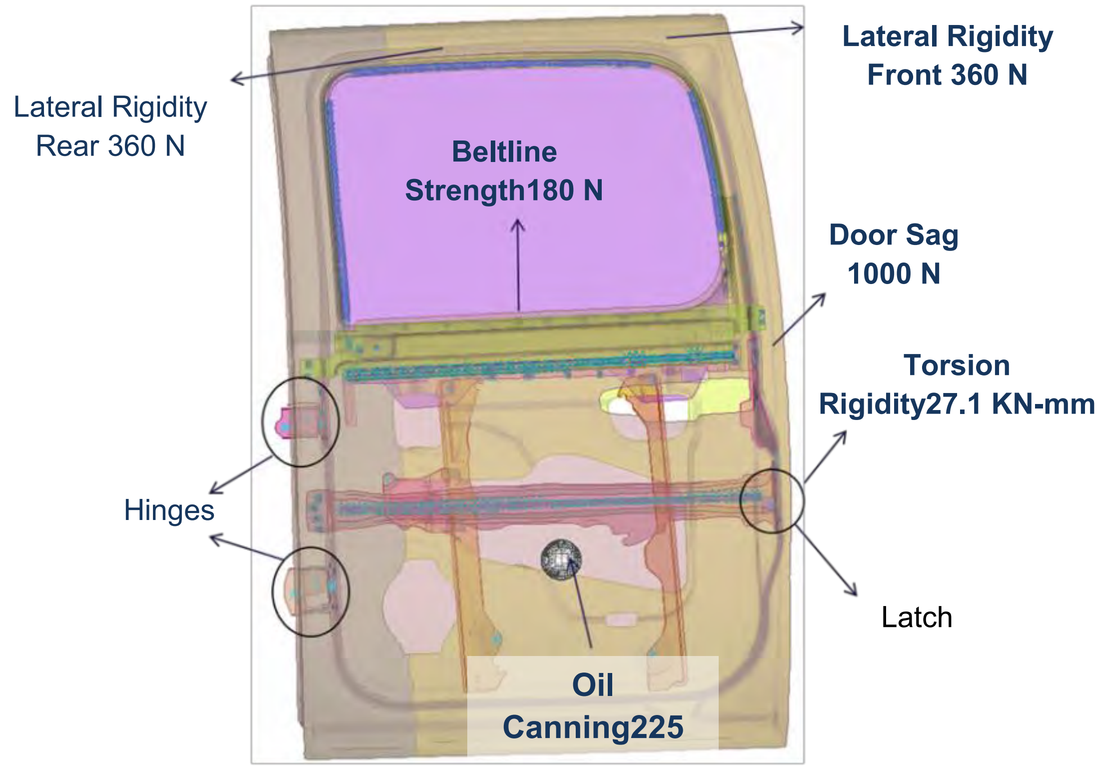



**Figure 4.18-93: Rear Door Loading and Boundary Conditions**

The loading and boundary conditions were created in the same procedure as explained for the front door using the same type of load quantities and constraints respectively.

The analysis results of the rear door performance study are provided in **Table 4.18-18**.

**Table 4.18-18: Rear Door Performance Results Baseline**

| No. | Loadcase | Target (mm) | Baseline Results (mm) |
|---|---|---|---|
| 1 | Frame Lateral Rigidity (Front) | <0.5 set | No set |
| 2 | Frame Lateral Rigidity (Rear) | <0.5 set | No set |
| 3 | Beltline Strength - Compression | <3.0 | 1.1 |
| 4 | Beltline Strength – Expansive | <3.0 | 1.0 |
| 5 | Torsional Rigidity | <4.0 | 3.8 |
| 6 | Door Sag | <2.0 set | 0.5 set |
| 7 | Oil Canning Load Deflection | <0.05 set | 0.025 |

It is observed that, when compared to the generic door performance targets, baseline rear door shows no significant deflections due to the frame loading. The baseline door deflections are within the acceptable range for the remaining loadcases. These performance measures are considered as baseline targets for the further iterations.

#### 4.18.4.1.3 Baseline Hood

The following loadcases were considered to analyze the hood strength and stiffness:

1) Cantilever Bending
2) Torsional Rigidity
3) Oil Canning Load Deflection

The FEA model of the hood was developed in ABAQUS non-linear solver format. The gauge and material grade maps of the hood are provided in **Figure 4.18-94** and **Figure 4.18-95**.

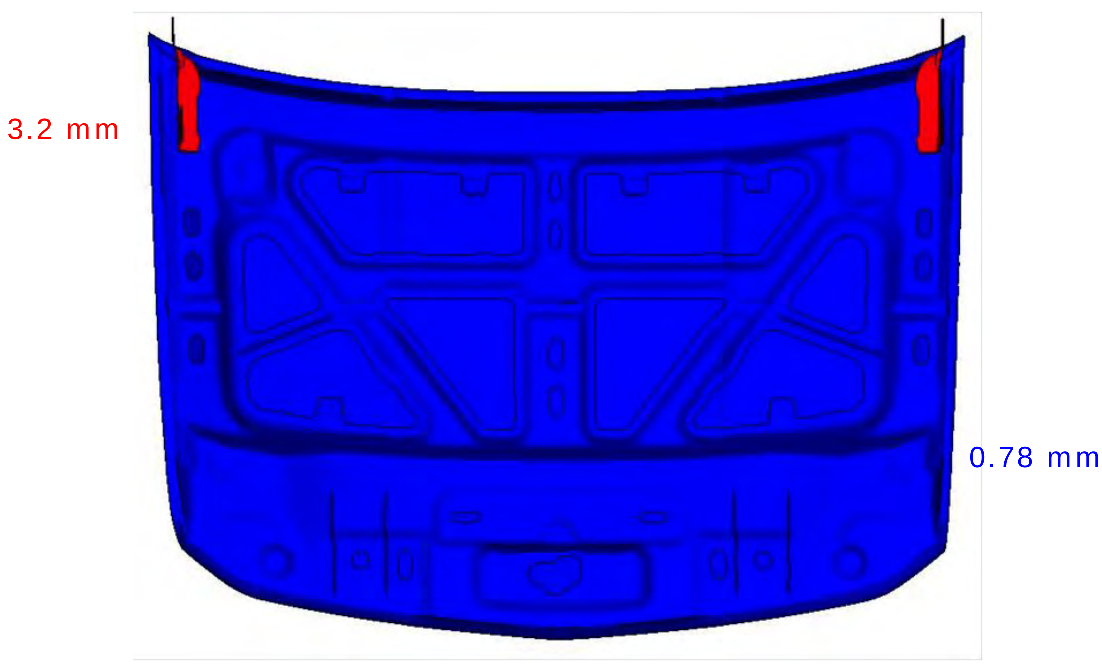



**Figure 4.18-94: Gauge Map of Hood**

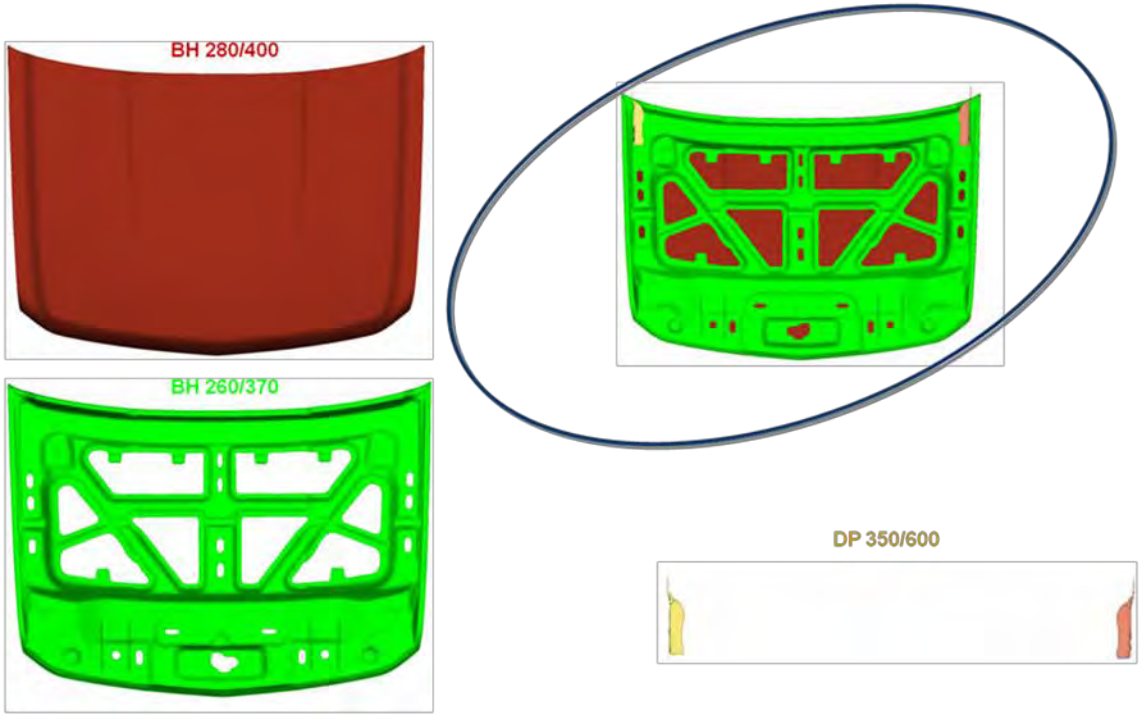



**Figure 4.18-95: Material Grade Map of Hood**

The hood FEA model was constrained and loaded as per the loadcase requirements. The necessary boundary conditions and loading conditions for the above loadcases are shown in **Figure 4.18-96**.

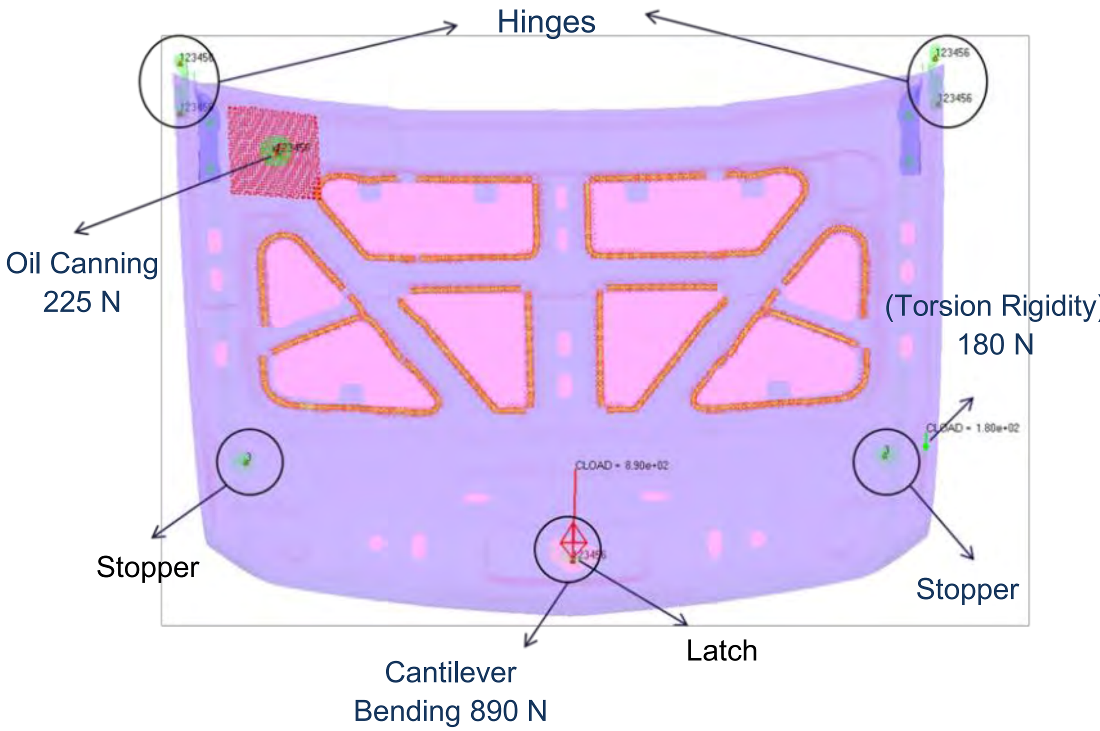



**Figure 4.18-96: Material Grade Map of Hood**

Cantilever bending simulation was carried out by applying a downward vertical load of 890 N at the latch point. The hood was constrained rigidly at hinges (DOF 1 to 6) and stoppers (DOF 3 only) accordingly.

Torsional rigidity of the hood was studied by applying a downward vertical loadof180 N at the driver side stopper. The hood was constrained at the hinges (DOF 1 to 6) and passenger side stopper (DOF 3 only) accordingly.

Oil canning load deflection is an important measure to study the hood deformation due to external pressures such as palm impression, thumb load, denting. The oil canning simulation was carried out to obtain the allowable deflection. A rigid circular pad was created over the hood outer panel. The rigid pad was allowed to move towards the hood (inboard engine direction) by applying a load 225 N in the normal direction of the loading area as shown in **Figure 4.18-96**. The hood was constrained at the hinges (DOF 1 to 6) and latches (DOF 1 to 6) accordingly.

The analysis results of the rear door performance study are provided in **Table 4.18-19**

**Table 4.18-19: Hood Performance Results Baseline**

| No. | Loadcase | Generic Target (mm) | Baseline Results (mm) |
|---|---|---|---|
| 1 | Cantilever Bending | <0.85 Set | 3.30E-03 |
| 2 | Torsional Rigidity | <35 | 8.83 |
| 3 | Oil Canning Load Deflection | <0.05 Set | no Set |

It is observed that, when compared to the generic hood performance targets, the baseline hood shows no significant deflections due to bending and oil canning load. The baseline hood deflections are within the acceptable range for the torsional loading. These performance measures are considered as baseline targets for the further iterations.

#### 4.18.4.1.4 Baseline Tailgate

The following loadcases were considered to analyze the tailgate (cargo box gate) strength and stiffness:

1) Torsional Rigidity
2) Oil Canning Load Deflection

The FEA model of the tailgate was developed in ABAQUS non-linear solver format. The gauge and material grade maps of the tailgate are provided in **Figure 4.18-97** and **Figure 4.18-98**.

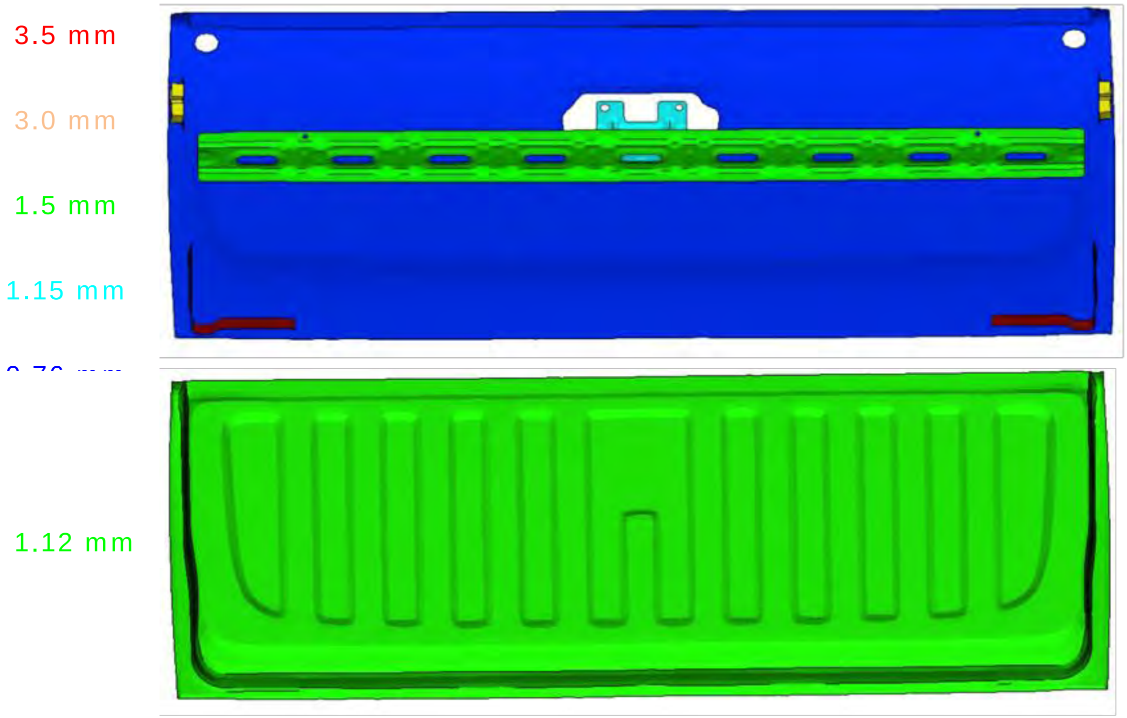



**Figure 4.18-97: Gauge Map of Tailgate**

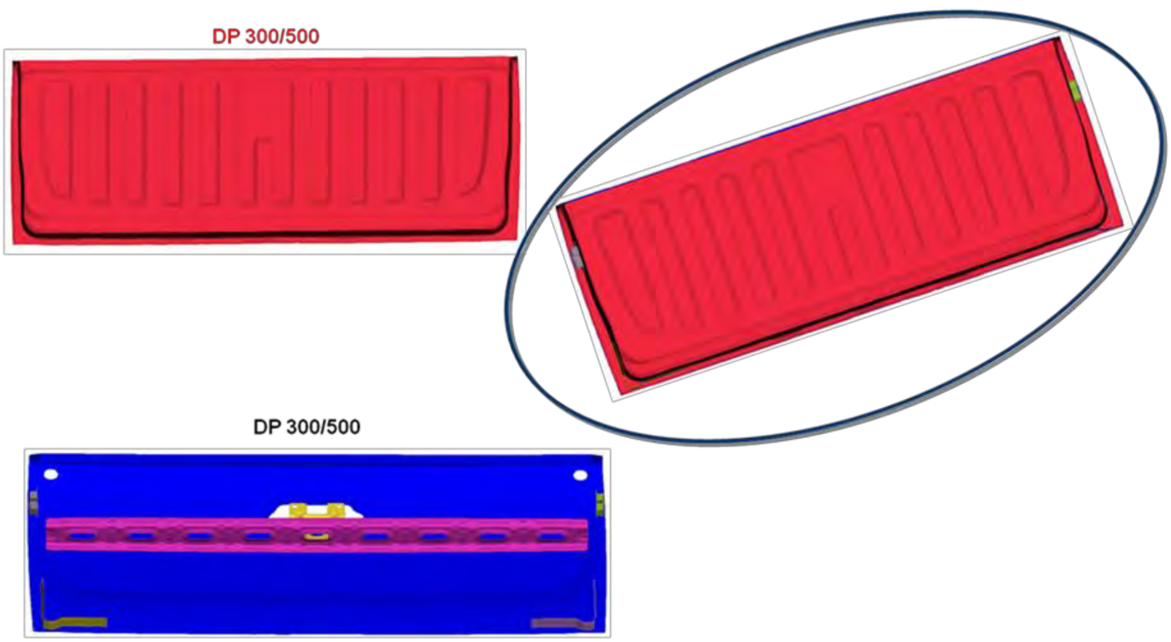



**Figure 4.18-98: Material Grade Map of Tailgate**

The tailgate FEA model was constrained and loaded as per the loadcase requirements. The necessary boundary conditions and loading conditions for the above loadcases are shown in **Figure 4.18-99**.

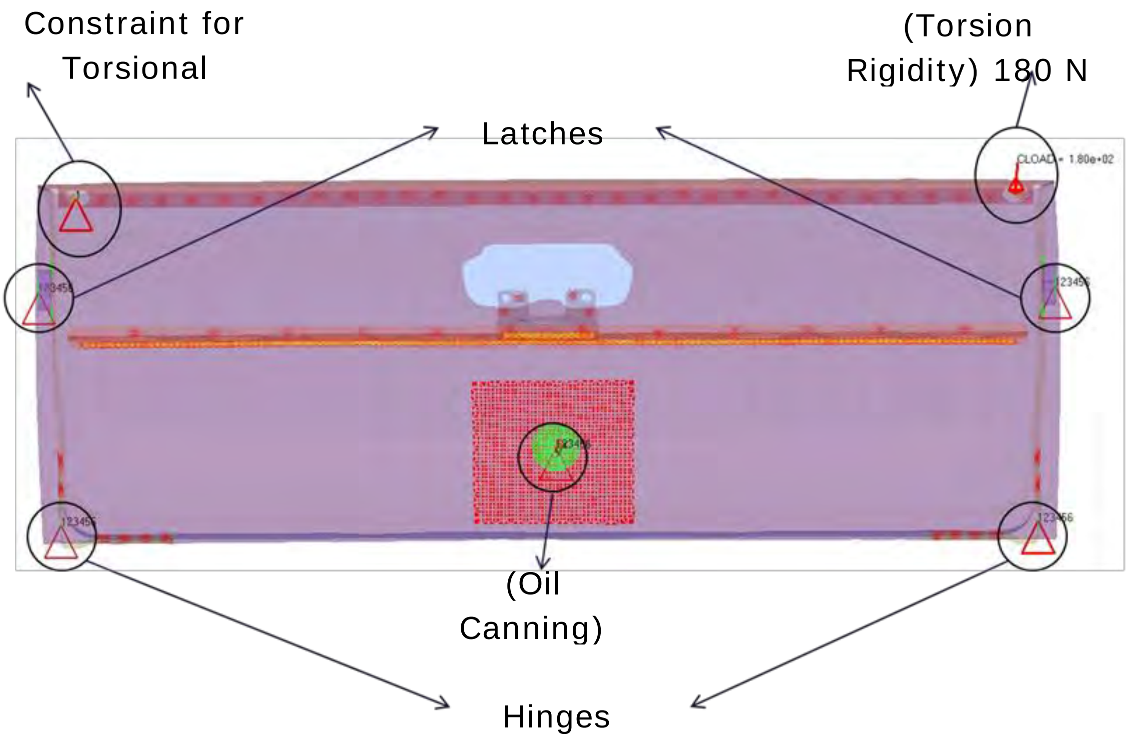



**Figure 4.18-99: Tailgate Loading and Boundary Conditions**

Torsional rigidity of the tailgate was studied by applying a load of 180 N in vehicle direction at the top corner of the tailgate (directly above the hinge). The tailgate was constrained at the hinges (DOF 1 to 6) and at the other top corner opposite to the torsion loading (DOF 1 only) accordingly as shown in **Figure 4.18-99**.

Similarly, the oil canning simulation was carried out to obtain the allowable deflection. A rigid circular pad was created over the tailgate outer panel. The rigid pad was allowed to move towards tailgate (inboard) by applying a load of 225 N in the normal direction of the loading area as shown in **Figure 4.18-99**. The tailgate was constrained at the hinges (DOF 1 to 6) and latches (DOF 1 to 6) accordingly.

The analysis results of the tailgate performance study are provided in **Table 4.18-20**.

**Table 4.18-20: Tailgate Performance Results Baseline**

| No. | Loadcase | Target (mm) | Baseline Results (mm) |
|---|---|---|---|
| 1 | Torsional Rigidity | <1.7 | 4.47E-01 |
| 2 | Oil Canning Load Deflection | <0.05 Set | 6.86E-03 |

It is observed that when compared to the generic tailgate performance targets, baseline tailgate shows no significant deflections due to torsion and oil canning load. The baseline tailgate deflections are within the acceptable range. These performance measures are considered as baseline targets for the further iterations.

### 4.18.5 Full Vehicle Optimization

In Phase 4 the results for the mass-reduce Silverado are reported along with the performance comparisons (i.e., NVH, Crash, Closure Structural Attributes) between the baseline Silverado and mass-reduced Silverado. In addition the incremental manufacturing costs for the mass-reduced Silverado Body and Frame systems/subsystems are provided at the end of this section.

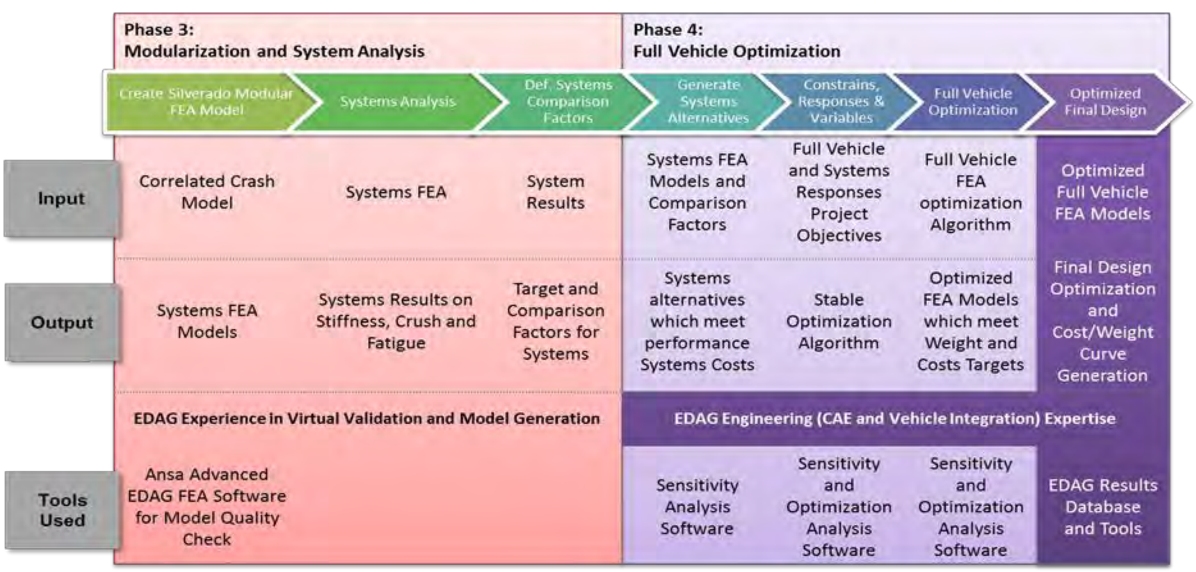



**Figure 4.18-100: Optimized Final Design**

#### 4.18.5.1 Optimized Body and Frame Mass reduction Overview

The outcome of the lightweight design optimization included the optimized frame, cabin, cargo box, bumpers, and closures and incorporated the following:

- Optimized gauge and material grades.
- Frame - Utilizing HSS/AHSS and aluminum materials
- Cabin - Utilizing HSS/AHSS and aluminum materials
- Cargo box - Utilizing aluminum materials
- TRBs on frame rails - mid and rear rails (inner and outer)
- Aluminum fender, radiator structure and IP cross-member assemblies
- Aluminum front and rear bumpers
- Doors - Utilizing HSS/AHSS and aluminum materials
- Aluminum hood
- Tailgate - Utilizing HSS/AHSS and aluminum materials

**Frame**

The gauge and material grade map of the optimized frame is shown in **Figure 4.18-101** and **Figure 4.18-102**.The frame also included TRB rails. The gauge and material grade map of the TRB rails have been provided in **Alternative Manufacturing Technology**. The TRB rail thickness range is about 2.5 - 3.5 mm. Strictly speaking, TRB rails weighed more than baseline parts, but it helped to integrate three different parts of the rail into one rail (inner/outer) and improved the stiffness performance.

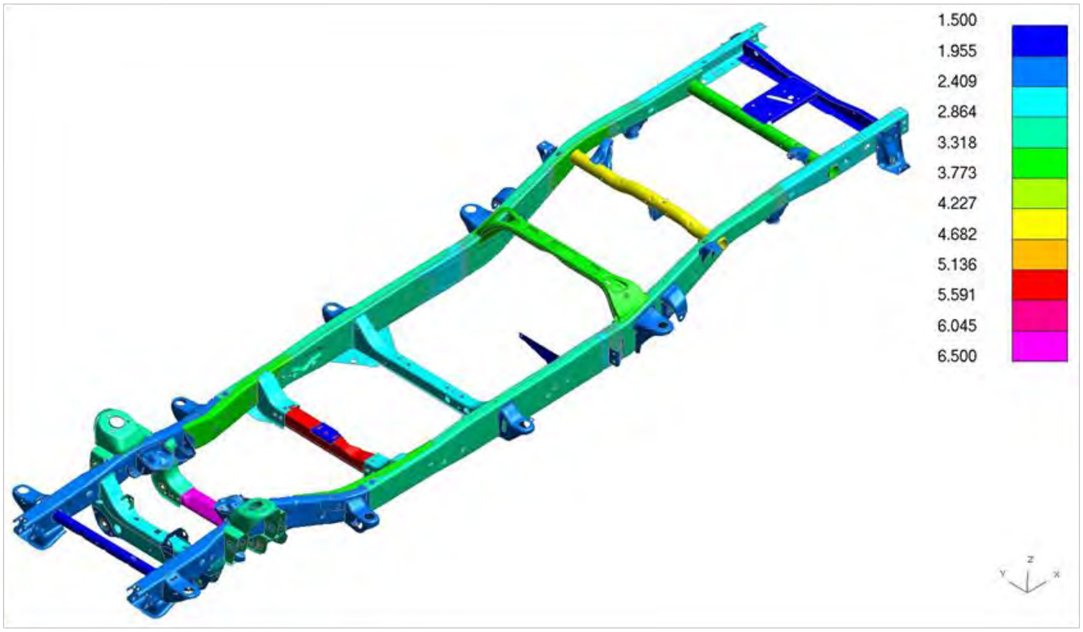



**Figure 4.18-101: Gauge Map of Optimized Frame**

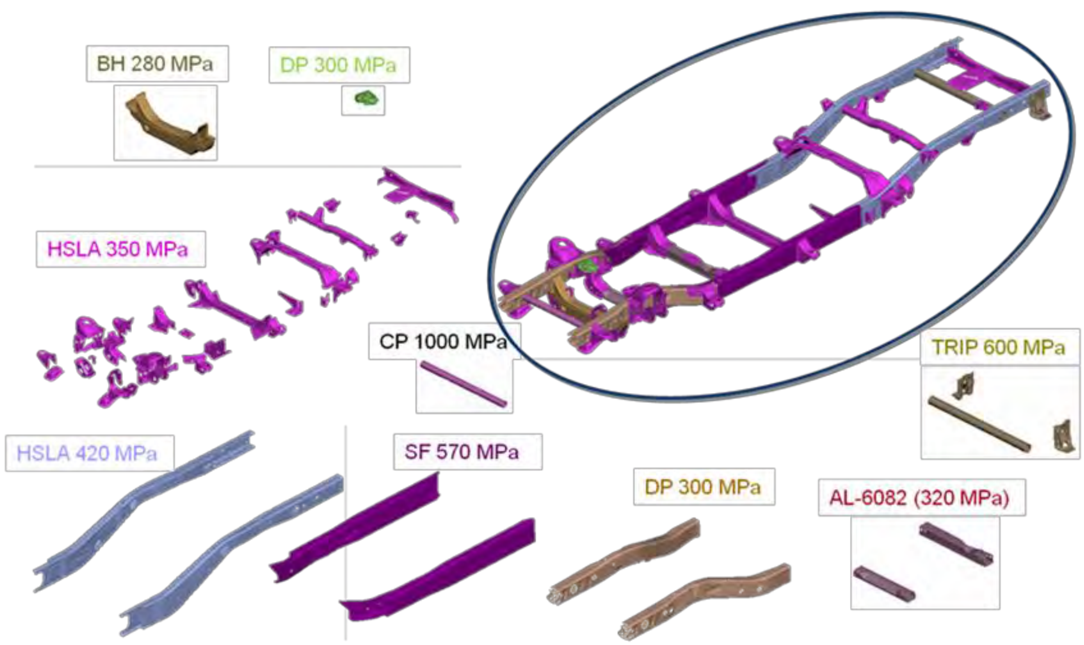
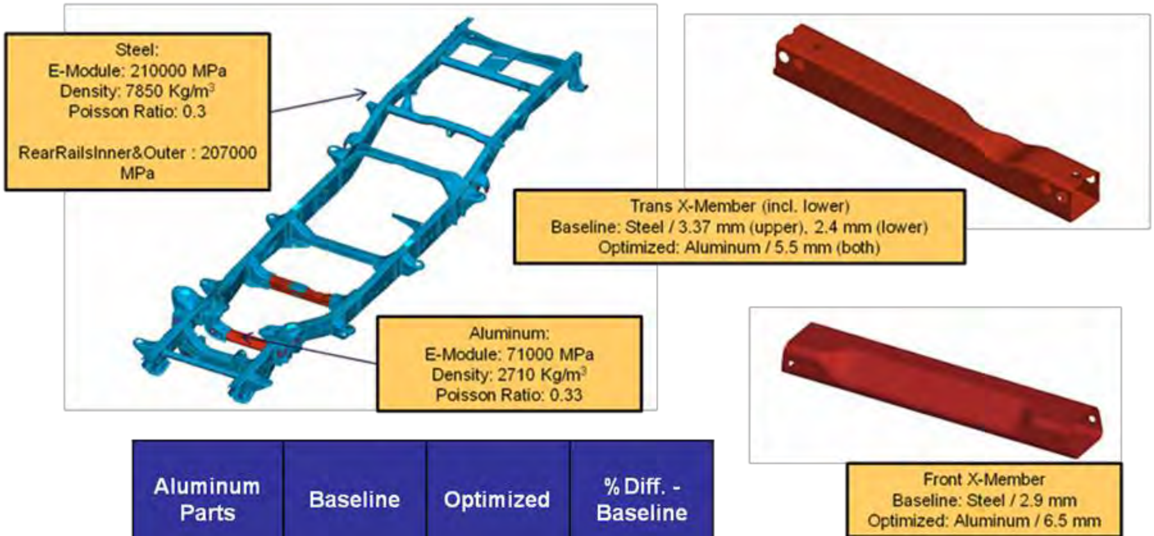



**Figure 4.18-102: Material Map of Optimized Frame**

The frame includes two aluminum parts, the front cross member and Trans cross member. The details of the aluminum cross members are given in **Figure 4.18-103**.




| Aluminum Parts | Baseline | Optimized | % Diff. - Baseline |
|---|---|---|---|
| Mass | 9.8 Kg | 6.6 Kg | -32.7% |

**Figure 4.18-103: Aluminum Cross Members of Frame**

It can be observed that the weight reduction, changing from baseline steel to aluminum cross member is very significant at about 32.7%.

## Cabin

The optimized cabin model have been developed based on a stamped riveted and bonded aluminum structure with castings at some of the highly loaded interfaces.

For the purpose of this study the panels are the same geometry as the base vehicle (i.e., a straight material and gauge substitution). The joining method used in the model is the same as the steel baseline with the same number of rivets / spot welds. The adhesive is not included in the NVH or crash models.

**Figure 4.18-104** and **Figure 4.18-105** indicate the gauge and material grade maps of the optimized cabin respectively.

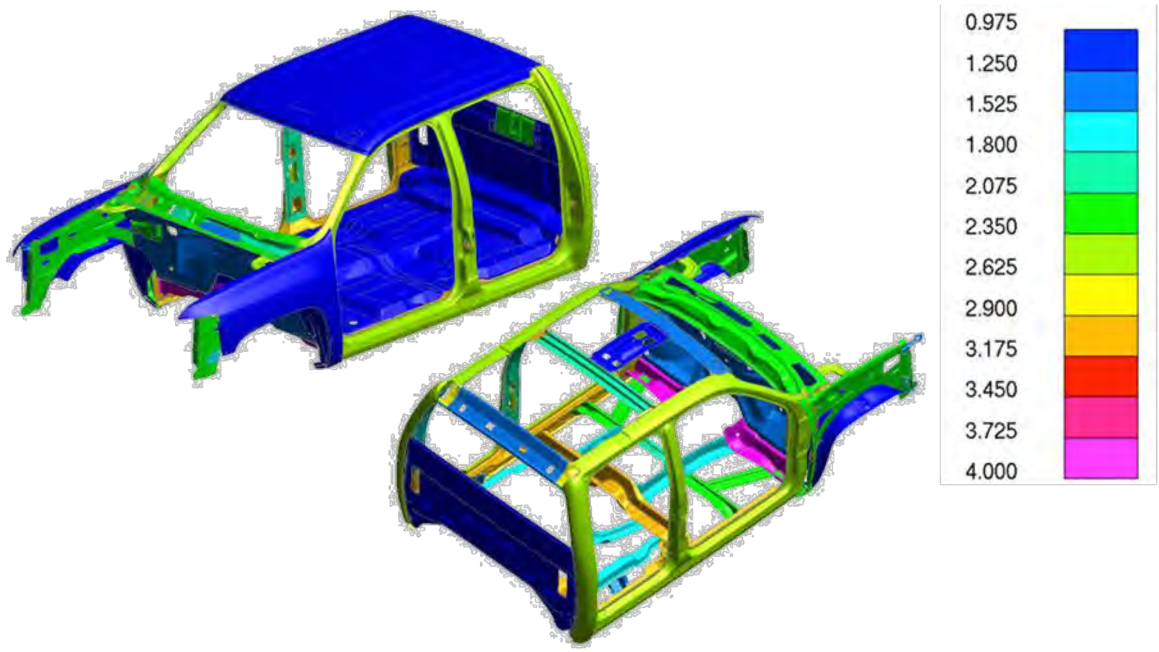



**Figure 4.18-104: Gauge Map of Optimized Cabin**

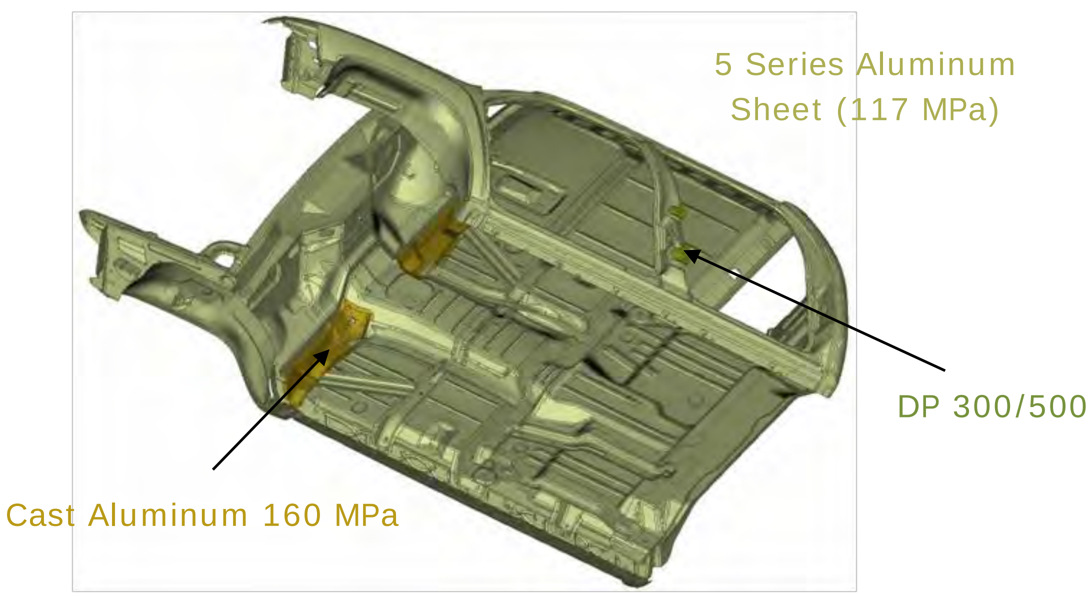



**Figure 4.18-105: Material Map of Optimized Cabin**

Further opportunities exist to use higher strength grades of steel in the cabin which in conjunction with geometrical design changes would allow further mass reduction and / or performance improvement.

#### 4.18.5.1.1 Cargo Box

**Figure 4.18-106** and **Figure 4.18-107** indicate the gauge and material grade maps of the optimized cargo box respectively.

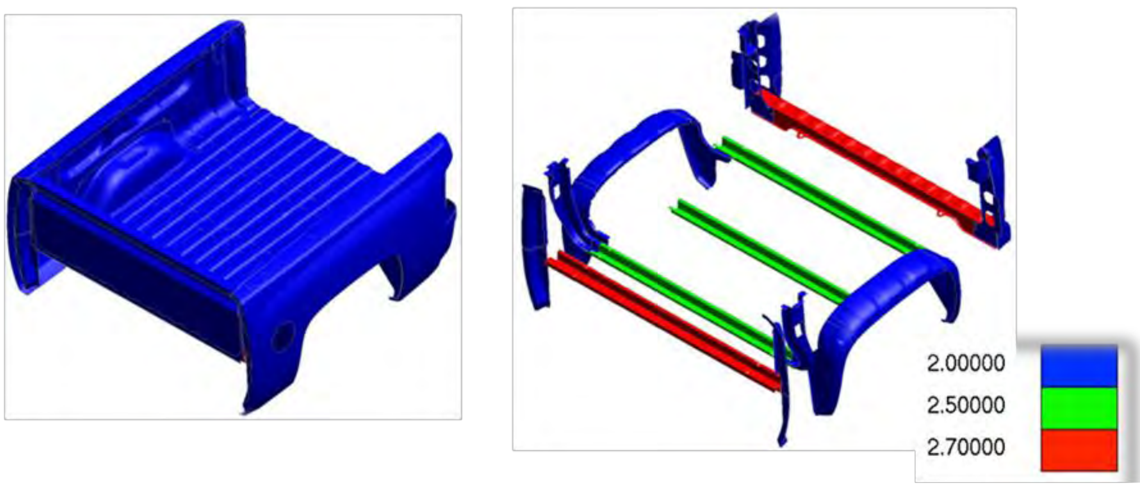



**Figure 4.18-106: Gauge Map of Optimized Cargo Box**


**Figure 4.18-107: Material Map of Optimized Cargo Box**

4.18.5.1.2 Bumper System

**Figure 4.18-108** and **Figure 4.18-109** indicate the gauge and material grade maps of the optimized front bumper respectively.

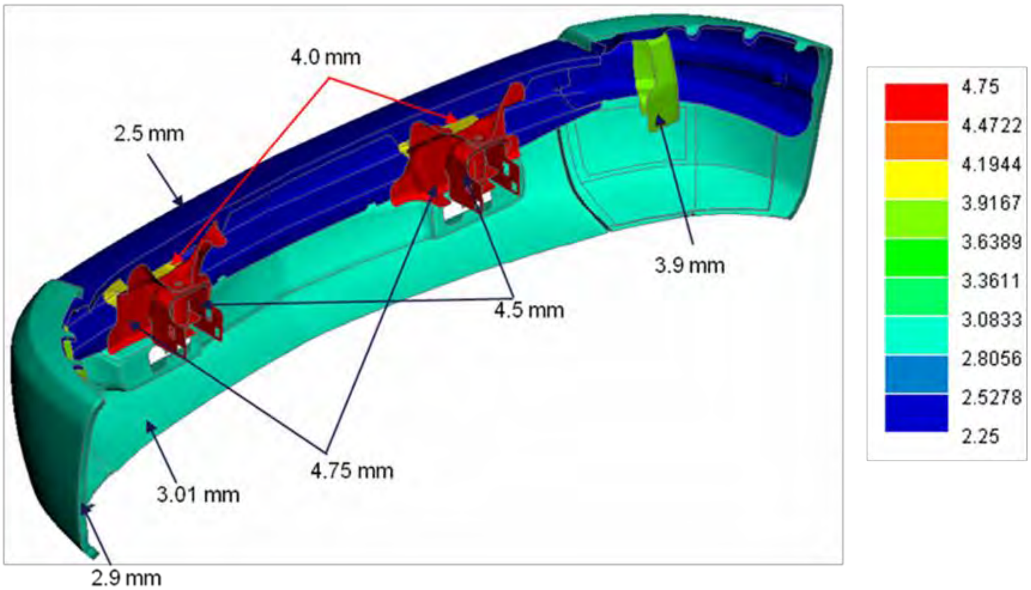



**Figure 4.18-108: Gauge Map of Optimized Front Bumper**

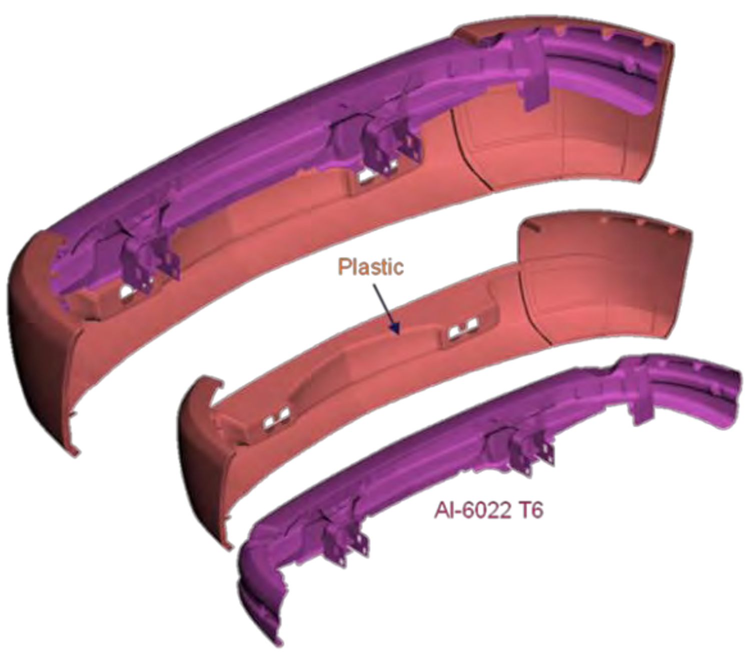



**Figure 4.18-109: Material Map of Optimized Front Bumper**

**Figure 4.18-110** and **Figure 4.18-111** indicate the gauge and material grade maps of the optimized rear bumper respectively.

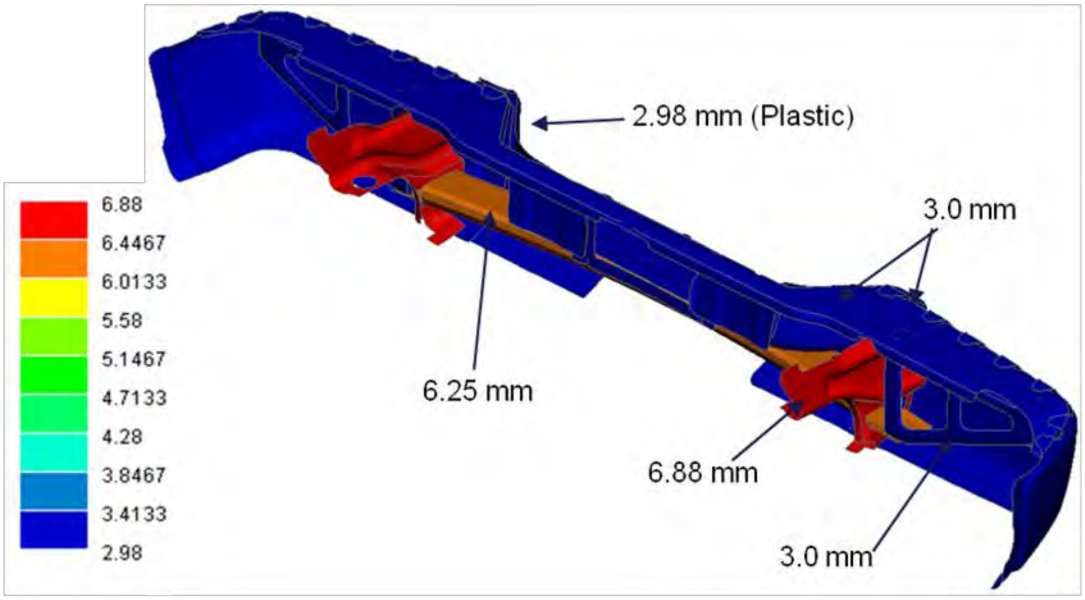



**Figure 4.18-110: Gauge Map of Optimized Rear Bumper**

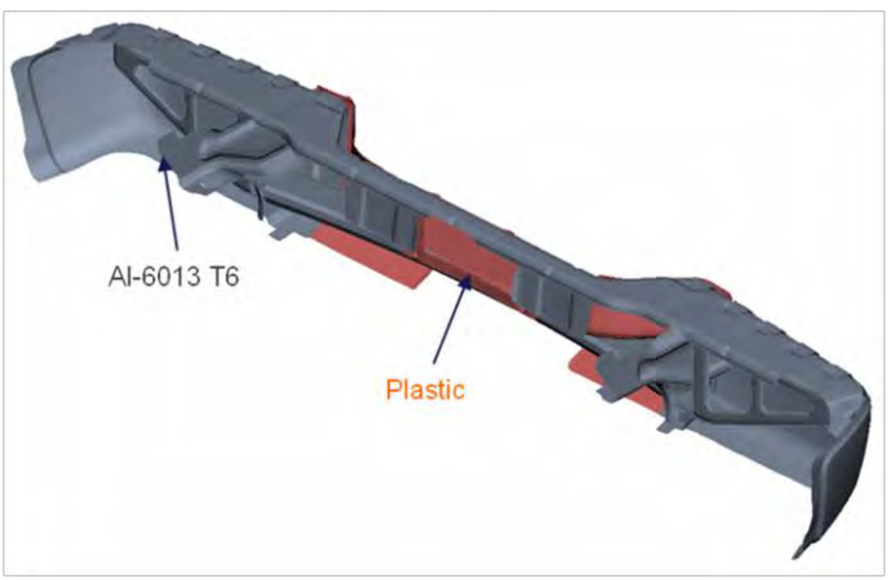



**Figure 4.18-111: Material Map of Optimized Rear Bumper**

### 4.18.5.1.3 Closures

**Figure 4.18-112** and **Figure 4.18-113** indicate the gauge and material grade maps of the optimized closures (doors, hood and cargo box gate) respectively.

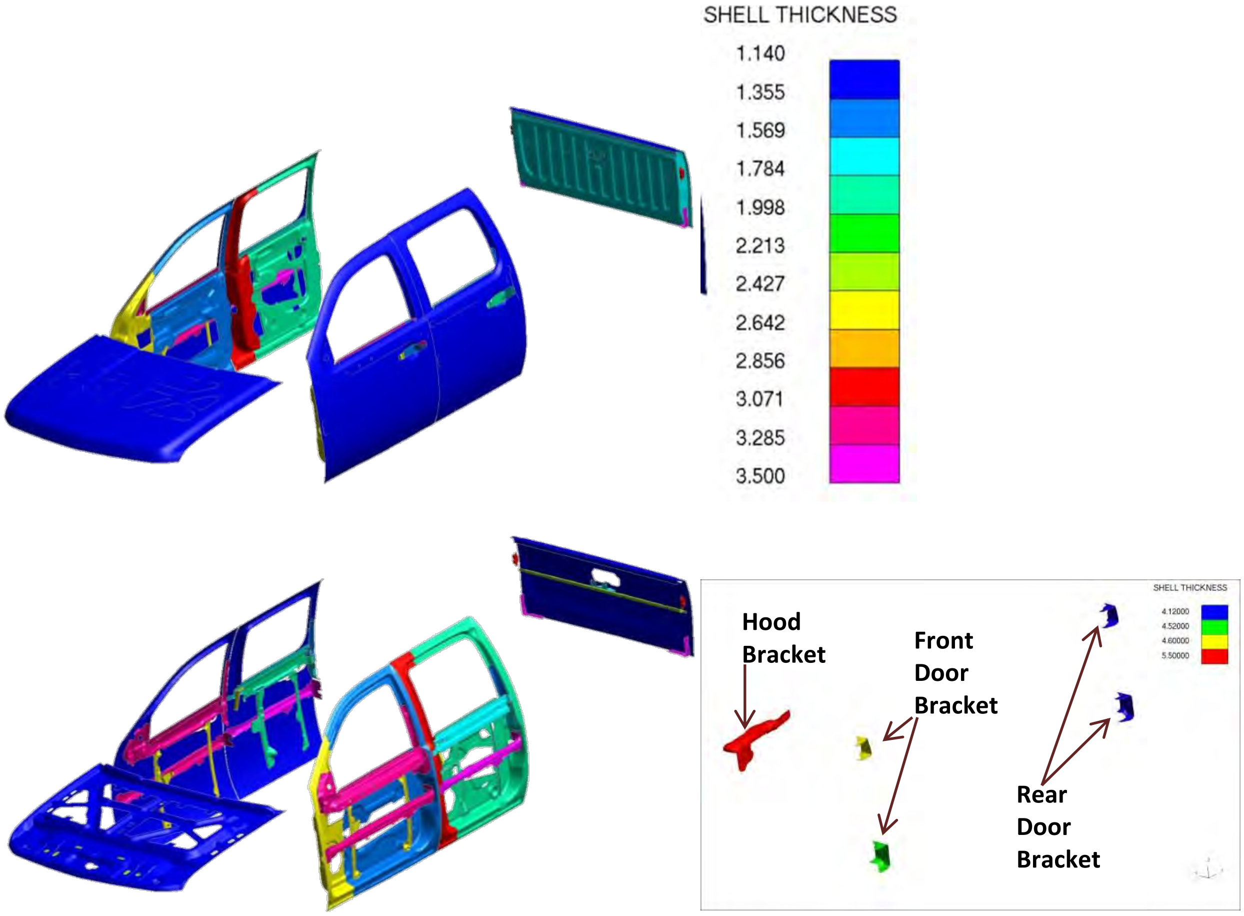



**Figure 4.18-112: Gauge Map of Optimized Closures**

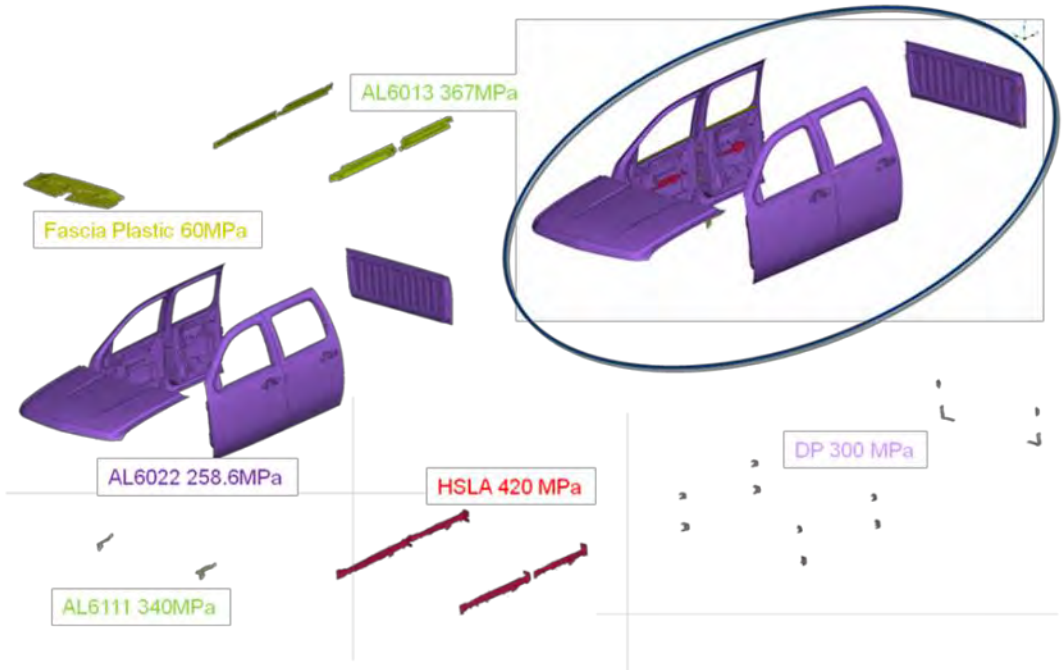



**Figure 4.18-113: Material Map of Optimized Closures**

**Figure 4.18-114** and **Figure 4.18-115** indicate the gauge and material grade maps of the optimized Instrument Panel (IP) cross member respectively.

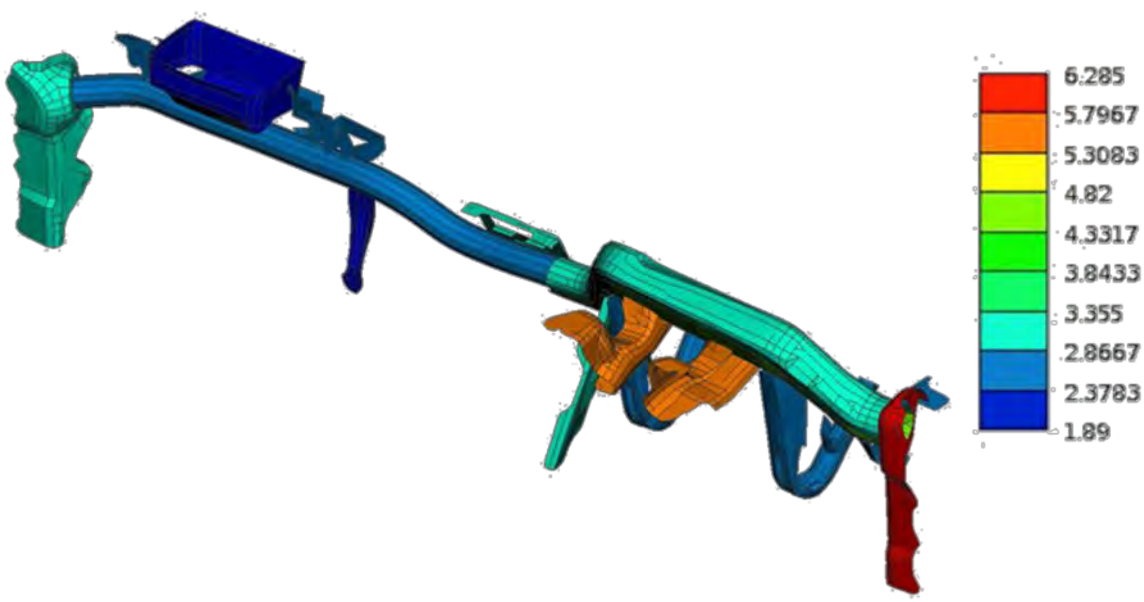



**Figure 4.18-114: Gauge Map of Optimized IP Cross Member**

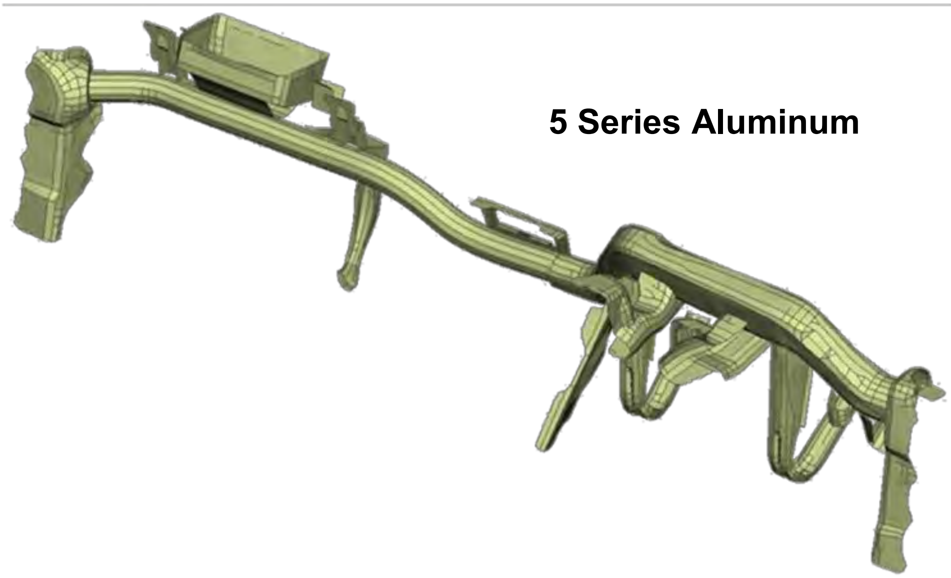



**Figure 4.18-115: Material Map of Optimized IP Cross Member**

4.18.5.1.4 Radiator Support

**Figure 4.18-116** and **Figure 4.18-117** indicate the gauge and material grade maps of the optimized radiator support (structure, extra cabin support) respectively.

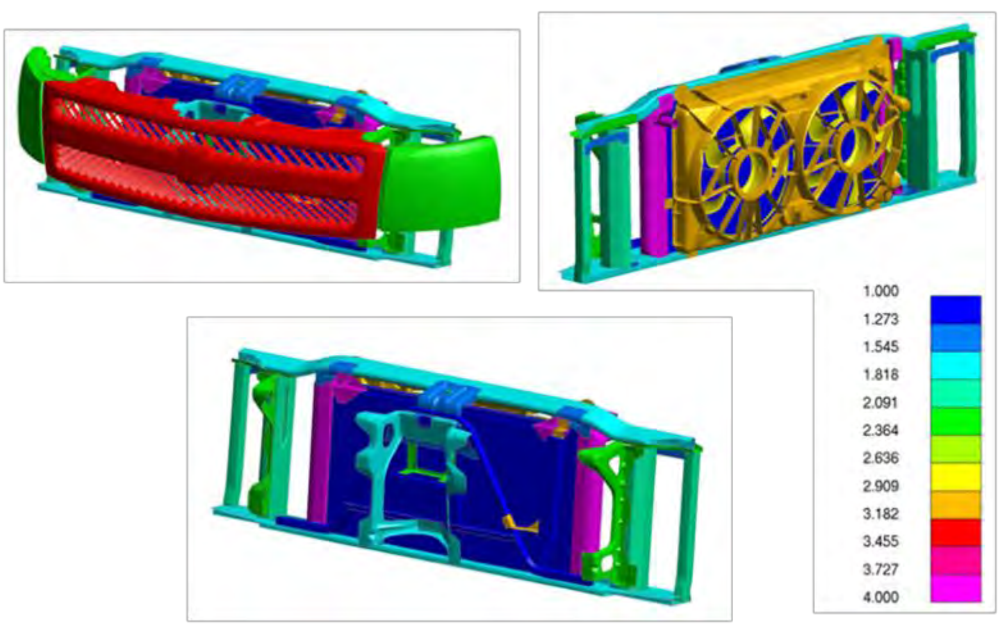



**Figure 4.18-116: Gauge Map of Optimized Radiator Support**

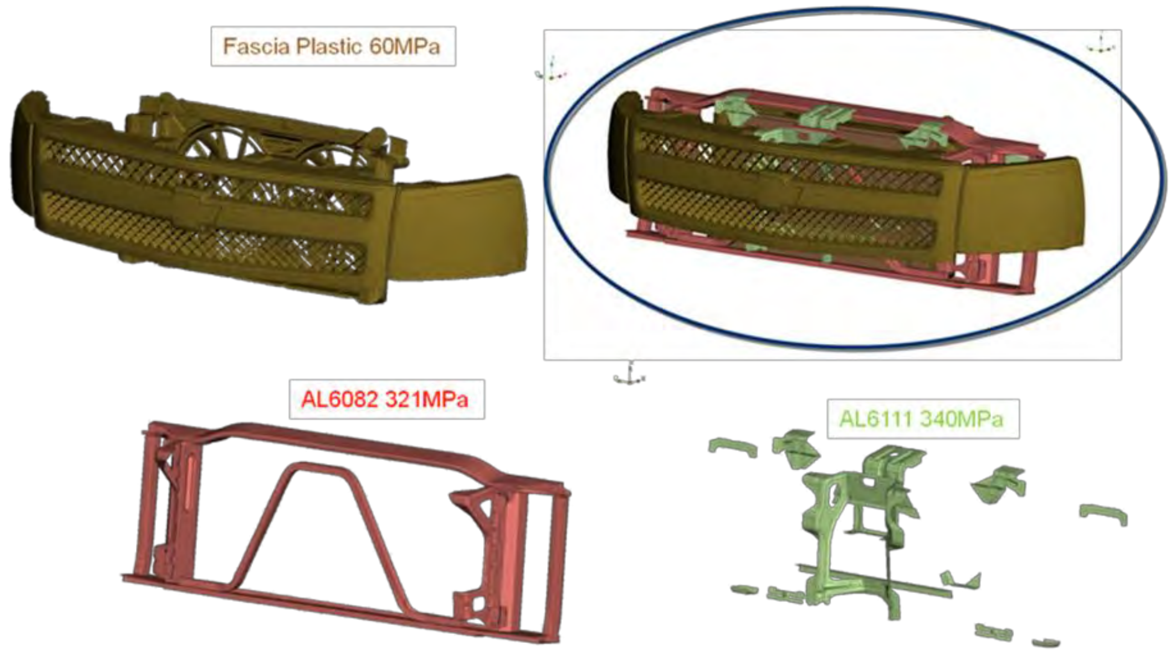



**Figure 4.18-117: Material Map of Optimized Radiator Support**

The major subassembly weights were calculated and tabulated with respect to the baseline weights. **Table 4.18-21** lists the major subassembly weights of the optimized model against the baseline model.

**Table 4.18-21: Optimized Weights**

| Silverado Models | | | |
|---|---|---|---|
| **System** | **Baseline Model Mass (kg)** | **Optimized Model Mass (kg)** | **Optimized compared to Baseline Model** |
| Box Assembly Pick-Up | 108.3 | 73.9 | 68.2% |
| Frame Assembly | 242.0 | 218.3 | 90.2% |
| Cabin | 207.2 | 131.8 | 63.6% |
| Panel Fender Outer LH | 14.9 | 7.4 | 49.7% |
| Panel Fender Outer RH | 14.0 | 7.0 | 50.0% |
| Radiator Structure | 12.9 | 7.2 | 55.8% |
| IP XMbr Beam Assembly | 12.1 | 6.3 | 52.1% |
| Extra Cabin - Radiator Support | 12.1 | 6.2 | 51.2% |
| **Sub-Total** | **623.5** | **458.1** | **73.5%** |
| **Mass Savings** | | **165.4** | |
| Bumper Front | 28.5 | 18.6 | 65.3% |
| Bumper Rear | 19.9 | 13.4 | 67.3% |
| Hood Assembly without Hinges | 22.7 | 11.7 | 51.5% |
| Door Assembly Front LH | 29.0 | 18.8 | 64.8% |
| Door Assembly Front RH | 28.9 | 18.8 | 65.1% |
| Door Assembly Rear LH | 22.0 | 15.0 | 68.2% |
| Door Assembly Rear RH | 22.2 | 15.0 | 67.6% |
| Cargo Box Gate | 18.8 | 10.2 | 54.3% |
| Sub-Total | 192.0 | 121.5 | 63.3% |
| **Mass Savings** | | **70.5** | |
| **Total Mass** | **815.5** | **579.6** | **71.1%** |
| **Total Mass Savings** | | **235.9** | |

The curb mass of the optimized model is 1,893 kg, which includes the combined 28.9% weight reduction from the systems listed in **Table 4.18-22**. It also includes a 21.1% mass reduction of the rest of the non-structural parts. This 21.1% reduction is an estimated weight reduction from trims and non-structural parts. The final weight distribution of the optimized full vehicle is tabulated in **Table 4.18-22**, showing the weight of the baseline and optimized models.

**Table 4.18-22: Final Weight Summary for Optimized Vehicle**

| Silverado Models | | | |
|---|---|---|---|
| | **Baseline Model Mass (kg)** | **Optimized Model Mass (kg)** | **Weight Reduced Percentage** |
| **System** | **Sub-Total** | **Sub-Total** | |
| FEV-Systems | | | |
| Chassis | 1638.5 | 1313.4 | 19.8% |
| Powertrain | | | |
| Electrical | | | |
| Body Interior | | | |
| EDAG-Systems | | | |
| Box Assembly Pick-Up | 623.5 | 458.1 | 26.5% |
| Frame Assembly | | | |
| Cabin | | | |
| Panel Fender Outer LH | | | |
| Panel Fender Outer RH | | | |
| Radiator Structure | | | |
| IP XMbr Beam Assembly | | | |
| Extra Cabin - Radiator Support | | | |
| Hood Assembly without Hinges | 143.6 | 89.5 | 37.7% |
| Door Assembly Front LH | | | |
| Door Assembly Front RH | | | |
| Door Assembly Rear LH | | | |
| Door Assembly Rear RH | | | |
| Cargo Box Gate | | | |
| Bumper Front | 48.4 | 32.0 | 33.9% |
| Bumper Rear | | | |
| **EDAG-Systems Total** | **815.5** | **579.6** | **28.9%** |
| **UVW** | **2454** | **1893** | **22.9%** |

The optimized weight of the body structure subsystems (frame, cabin, cargo box, fenders, IP cross member assembly, and radiator assembly) is 458.1 kg when compared to baseline weight of 623.5 kg. This is 165.4 kg (26.5%) reduction. The optimized weight of the closure subsystems (hood, doors, and tailgate) is 89.5 kg when compared to baseline weight of 143.6 kg. This is 54.1 kg (37.7%) reduction. The optimized weight of the bumpers is 32.0 kg when compared to baseline weight of 48.4 kg. This is 16.4 kg (33.9%) reduction. Therefore, the systems included in the EDAG portion of this study were reduced by 235.9 kg (28.9%).

The optimization outcome was validated by carrying out further CAE simulations on the optimized model. The optimized NVH and crash models were directly carried over from the optimizer and appropriate loadcases were setup. The remaining loadcase models were updated by incorporating the necessary data from optimization. The following sections explain the NVH, durability, crash and vehicle dynamic model results in comparison to the baseline results.

### 4.18.5.2 NVH Performance Results

The NVH models of frame, cab, cargo box BIPs (containing only BIW parts and a few bolt-on parts as explained earlier), and full BOF (containing frame, cabin, cargo box, bumpers and trailer hitch) configurations were once again subjected to static bending and static torsion simulations by incorporating the optimization outcome. **Table 4.18-23** through **Table 4.18-26** provide the results of the optimized models for bending stiffness and torsion stiffness loadcases.

**Table 4.18-23: NVH Results Summary for Optimized Frame Model**

| Study Description | Weight (Kg) | Torsion Stiffness (KN.m/rad) | Bending Stiffness (N/mm) | Comments |
|---|---|---|---|---|
| EDAG CAE Model Baseline Frame | 242.0 | 190.3 | 2,983 | CAE Model of 2011 Silverado Frame same configuration as Test Vehicle |
| EDAG CAE Model Optimized Frame | 218.3 | 189.6 | 3,213 | CAE Model of 2011 Silverado Frame same configuration as Baseline |
| Percentage of Optimized Model to Baseline | 90.2% | 99.6% | 107.7% | Comparison between Baseline and Optimized Model |

**Table 4.18-24: NVH Results Summary for Optimized Cabin Model**

| Study Description | Weight (Kg) | Torsion Stiffness (KN.m/rad) | Bending Stiffness (N/mm) | Comments |
|---|---|---|---|---|
| EDAG CAE Model Baseline Cabin | 207.2 | 1,021.5 | 7,060 | CAE Model of 2011 Silverado Cabin same configuration as Test Vehicle |
| EDAG CAE Model Optimized Cabin | 131.8 | 1,058.4 | 6,872 | CAE Model of 2011 Silverado Cabin same configuration as Baseline |
| Percentage of Optimized Model to Baseline | 63.6% | 103.6% | 97.3% | Comparison between Baseline and Optimized Model |

**Table 4.18-25: NVH Results Summary for Optimized Cargo Box Model**

| Study Description | Weight (Kg) | Torsion Stiffness (KN.m/rad) | Bending Stiffness (N/mm) | Comments |
|---|---|---|---|---|
| EDAG CAE Model Baseline Cargo Box | 108.3 | 219.8 | 2,324 | CAE Model of 2011 Silverado Box same configuration as Test Vehicle |
| EDAG CAE Model Optimized Cargo Box | 73.9 | 214.0 | 3,039 | CAE Model of 2011 Silverado Box same configuration as Baseline |
| Percentage of Optimized Model to Baseline | 68.2% | 97.4% | 130.8% | Comparison between Baseline and Optimized Model |

**Table 4.18-26: NVH Results Summary for Optimized BOF Model**

| Study Description | Weight (Kg) | Torsion Stiffness (KN.m/rad) | Bending Stiffness (N/mm) | Comments |
|---|---|---|---|---|
| EDAG CAE Model Baseline BOF | 691.6 | 282.3 | 5,337 | CAE Model of BOF combined configuration of 2007, 2011 Test Vehicles |
| EDAG CAE Model Optimized BOF | 526.7 | 272.8 | 5,498 | CAE Model of BOF same configuration as Baseline |
| Percentage of Optimized Model to Baseline | 76.2% | 96.6% | 103.0% | Comparison between Baseline and Optimized Model |

From these tables it can be seen that the NVH performance of the optimized CAE models are very similar to the baseline models in terms of both torsion and bending loadcases while meeting the <5% comparison requirement. The optimized frame model shows improvements in performance with 9.8% weight reduction. The optimized cabin (all aluminum except hinges) model shows 3.6% improvement in torsion characteristics and a 0.8% improvement in bending characteristics. The optimized cargo box shows a slight reduction in performance for torsional characteristics, however it is within the allowable limit of <5%. However, greater performance improvement is observed in bending characteristics with significantly higher weight reduction of 31.8%. Similarly, the full BOF model shows a performance change in torsional stiffness, but it is well within the allowable limits, whereas the bending performance shows a 3.2% improvement.

#### 4.18.5.3 Crash Performance Results

The optimized crash model was validated further for the following seven different crash loadcases and compared with the results of baseline models respectively.

1) FMVSS 208 – 35 mph flat frontal crash (US NCAP)
2) IIHS – 40 mph ODB frontal crash
3) FMVSS 214 – 38.5 mph MDB side impact (US SINCAP)
4) IIHS – 31 mph MDB side impact
5) FMVSS 214 – 20 mph5th Percentile pole side impact
6) FMVSS 301 – 50 mph MDB rear impact
7) FMVSS 216a – Roof crush (utilizing IIHS roof-crush criteria)

The model setup and test requirements were maintained consistent to that of EDAG baseline models, as explained earlier.

**1) FMVSS 208 – 35 mph flat frontal crash (US NCAP)**

**Deformation Mode**

The deformation modes at 150ms (end of crash event) of the optimized model were compared to that of the baseline model. The deformation modes are presented in **Figure 4.18-118** through **Figure 4.18-122**. The left-hand side illustrations show the deformation modes of the baseline model and the right-hand side illustrations show the deformation modes of the optimized model.

Observing the exterior vehicle deformation mode comparisons indifferent views, the optimized model shows similar characteristics in structural deformation.


**Figure 4.18-118: Deformation Mode Left Side View at 150ms**


**Figure 4.18-119: Deformation Mode Front View at 150ms**

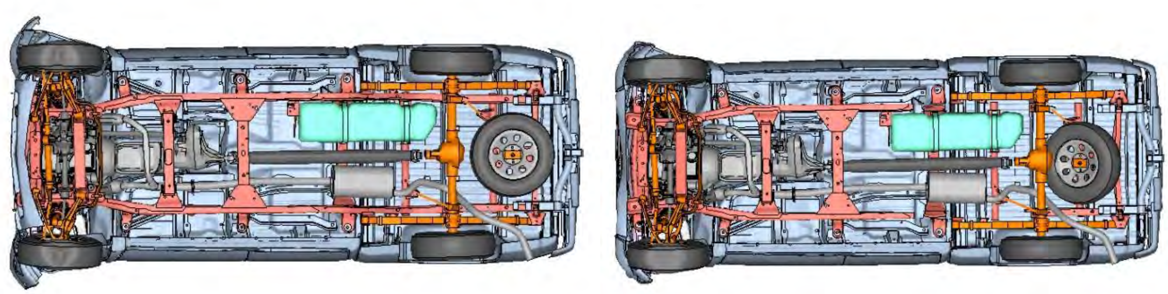


**Figure 4.18-120: Deformation Mode Bottom View at 150ms (Baseline, left; Optimized, right)**


**Figure 4.18-121: Deformation Mode ISO View at 150ms**

The underbody structural deformation modes are compared as shown in **Figure 4.18-122**.

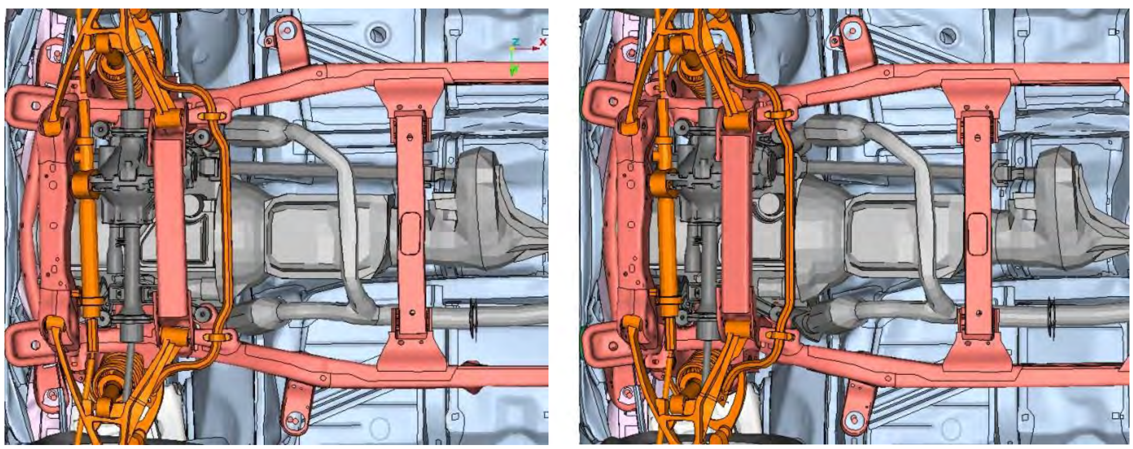


**Figure 4.18-122: Deformation Mode Underbody View at 80ms (Baseline, left; Optimized, right)**

## Crash Pulse

**Figure 4.18-123** through **Figure 4.18-125** show the comparisons of acceleration, velocity and displacement of the optimized and baseline models with the results summarized in **Table 4.18-27**.

The pulse shape overall is similar between the models however the balance in crush load in the front rails and the secondary crush (behind the front suspension mount) has resulted in a slightly stiffer pulse in the 50-60ms region. The low acceleration pulse in the 0-20ms range is due to the balance between the primary energy absorption in the front rails and the absorbed in the secondary crush (behind the front suspension mount).

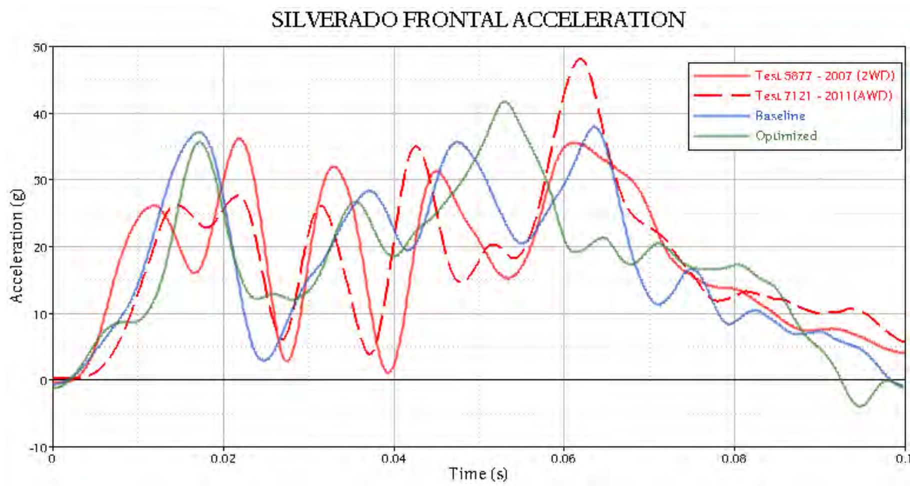



**Figure 4.18-123: CAE Comparison Baseline vs. Optimized**

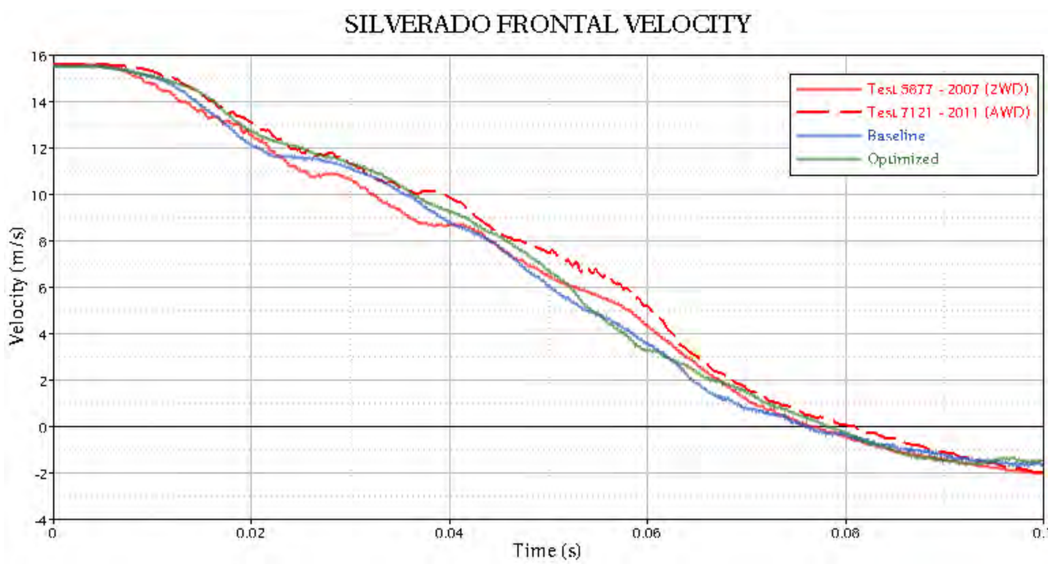



**Figure 4.18-124: CAE Comparison Baseline vs. Optimized**

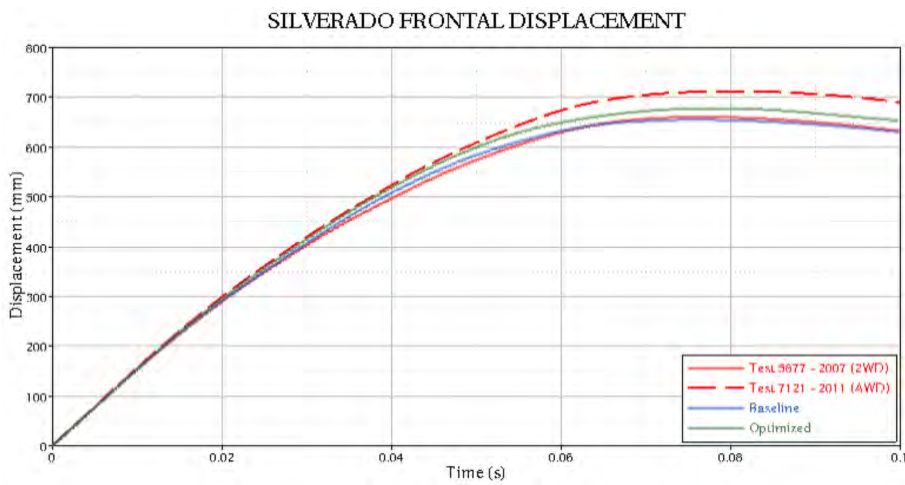



**Figure 4.18-125: CAE Comparison Baseline vs. Optimized**

**Table 4.18-27: Pulse and Dynamic Crush**

| No. | Frontal crash Measurements | Silverado Test | Baseline | Optimized |
|---|---|---|---|---|
| 1 | Dynamic Crush (mm) | 655 - 717 | 655.5 | 701.4 |
| 2 | T (to zero) (ms) | 75.0-80.5 | 75.9 | 78.2 |
| 3 | Pulse (G's) | 37.7 - 48.1 | 37.9 | 47.3 |

## Intrusion

The dash intrusions are summarized in **Table 4.18-28**.

**Table 4.18-28: Dash Intrusion Comparison Baseline vs. Optimized**

| No. | Intrusion | Test (mm) | Baseline (mm) | Optimized (mm) |
|---|---|---|---|---|
| 1 | Door Opening | 6 - 4 | 6.3 | 0.7 |
| 2 | Driver Footrest | no data | 31.9 | 28.8 |
| 3 | Driver Toe Pan Left | no data | 34.5 | 47.1 |
| 4 | Driver Toe Pan Center | no data | 43.7 | 73.5 |
| 5 | Driver Toe Pan Right | no data | 44.6 | 82.9 |

4.18.5.3.1 IIHS—40 mph ODB Frontal Crash

**Deformation Mode**

The deformation modes at 150ms (end of crash event) of the optimized model were compared to that of the baseline model. The deformation modes are presented in **Figure 4.18-126** through **Figure 4.18-128**. The left-hand side illustrations show the deformation modes of the baseline model and the right-hand side illustrations show the deformation modes of the optimized model.

Observing the exterior vehicle deformation mode comparisons in different views, the optimized model shows similar characteristics of structural deformation.

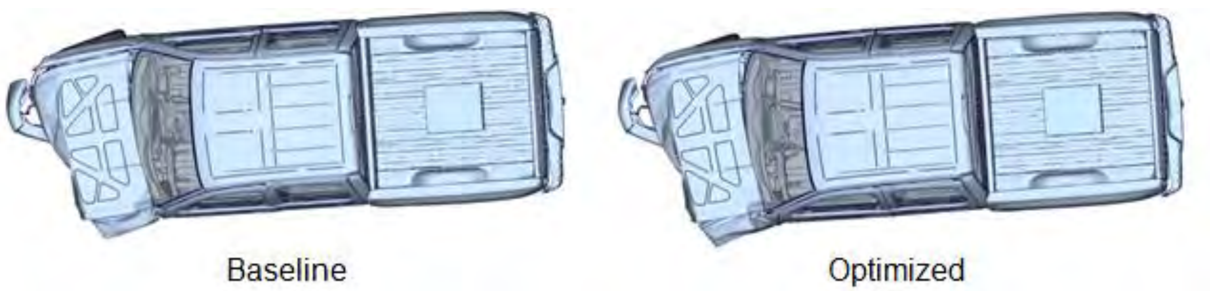



**Figure 4.18-126: Deformation Mode Top View at 150ms**

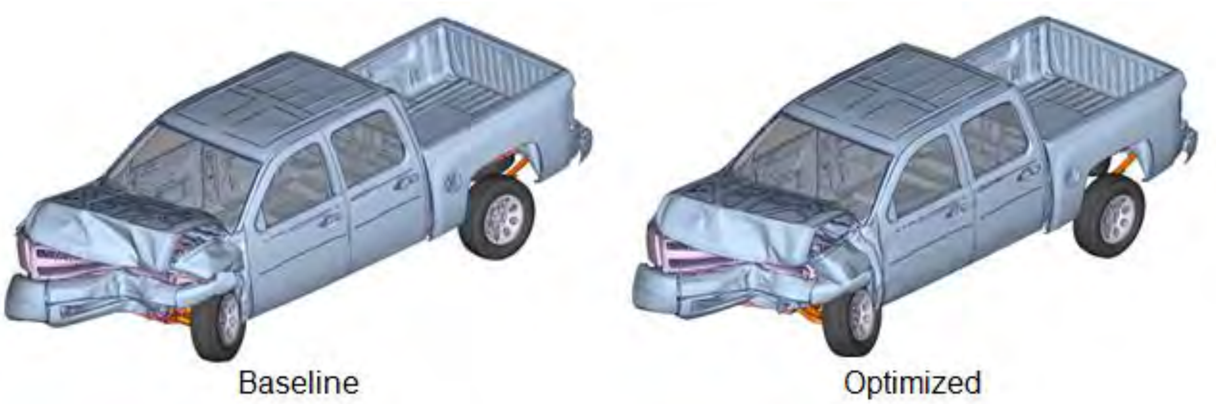



**Figure 4.18-127: Deformation Mode ISO View at 150ms**


**Figure 4.18-128: Deformation Mode Left Side View at 150ms**

The underbody structural deformation modes are compared as shown **Figure 4.18-129** and **Figure 4.18-130**, where it can be seen the optimized model shows the same level of deformation as that of the baseline target. The compartment area is well protected from significant deformation in both the optimized and baseline models. From the deformation modes, it is also noted the crush energy is absorbed by the engine compartment, rails, and front cradle.

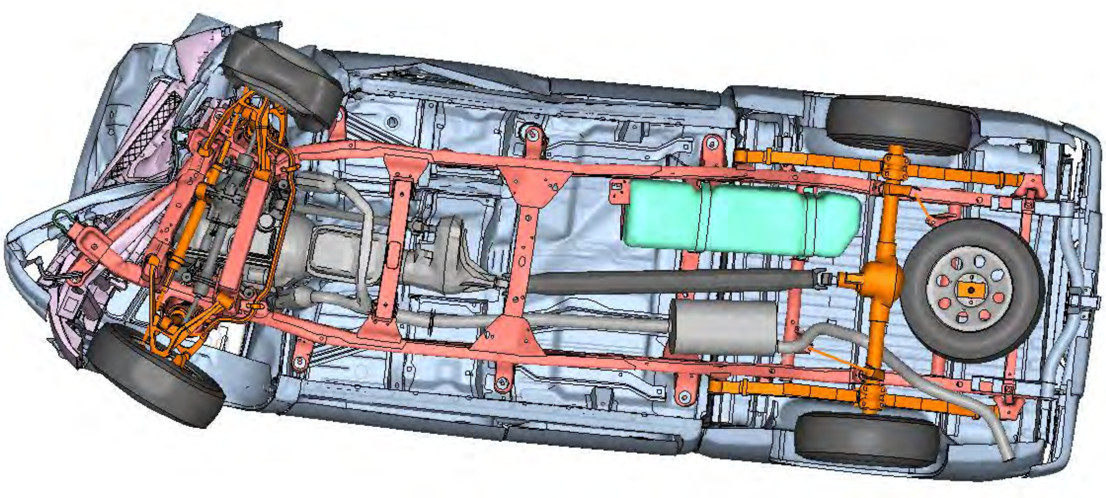


**Figure 4.18-129: Deformation Mode Bottom View at 150ms – Baseline**

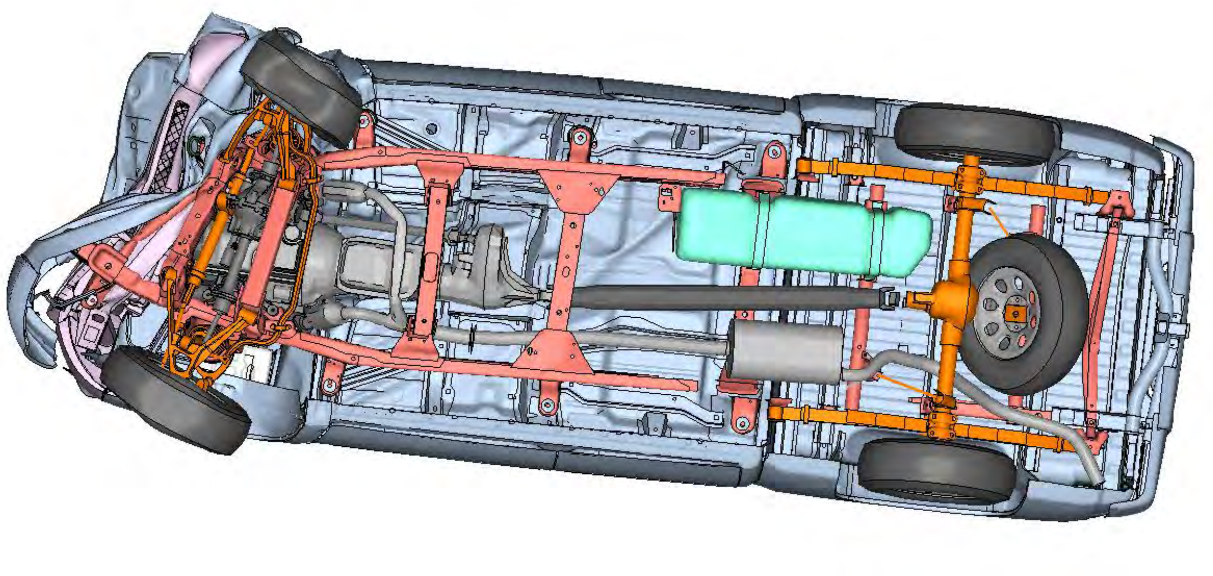


**Figure 4.18-130: Deformation Mode Bottom View at 150ms - Optimized**

## Crash Pulse

**Figure 4.18-131** shows the pulse comparison between the optimized model and the baseline model.

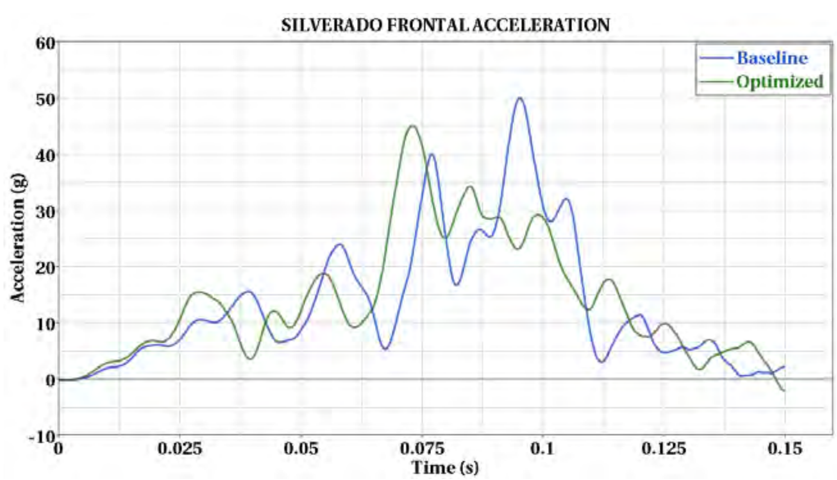



**Figure 4.18-131: CAE Comparison Baseline vs. Optimized**

In this case, the optimized model shows a similar level of performance to the baseline model in terms of crash pulse.

## Dynamic Crush

The deformation indicator of the vehicle structure dynamic crash is compared in **Figure 4.18-132** and **Figure 4.18-133**. The total dynamic crush shown in **Figure 4.18-132** includes the barrier deformation.

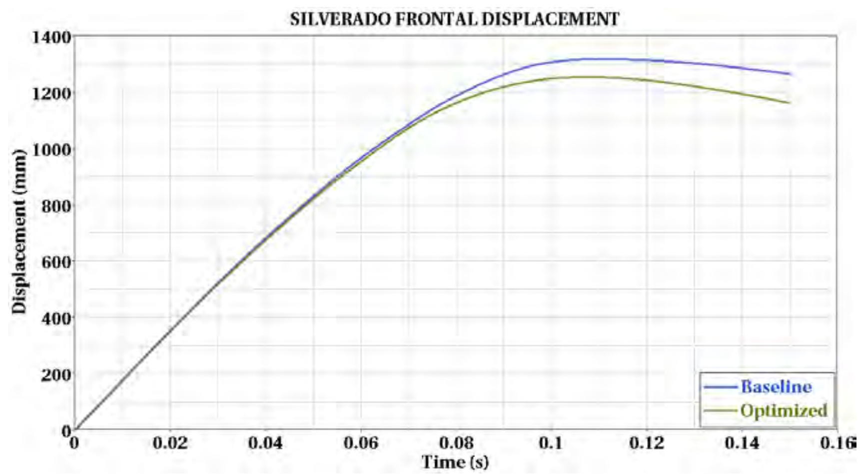



**Figure 4.18-132: CAE Comparison Baseline vs. Optimized (with Barrier Deformation)**

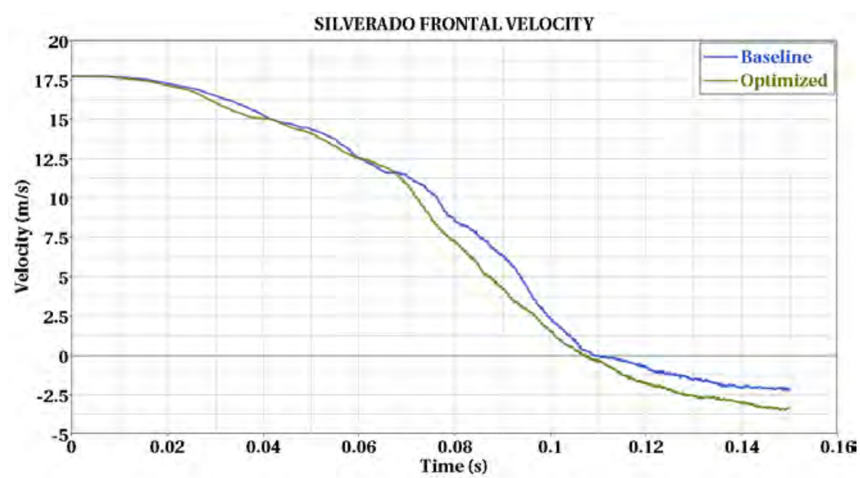



**Figure 4.18-133: CAE Comparison Baseline vs. Optimized**

## Dash Panel Intrusions

The compartment dash panel intrusions measured at the footrest, toe pan, instrument panel cross member, and door openings are plotted with respect to the performance rating chart and is shown in **Figure 4.18-134**.

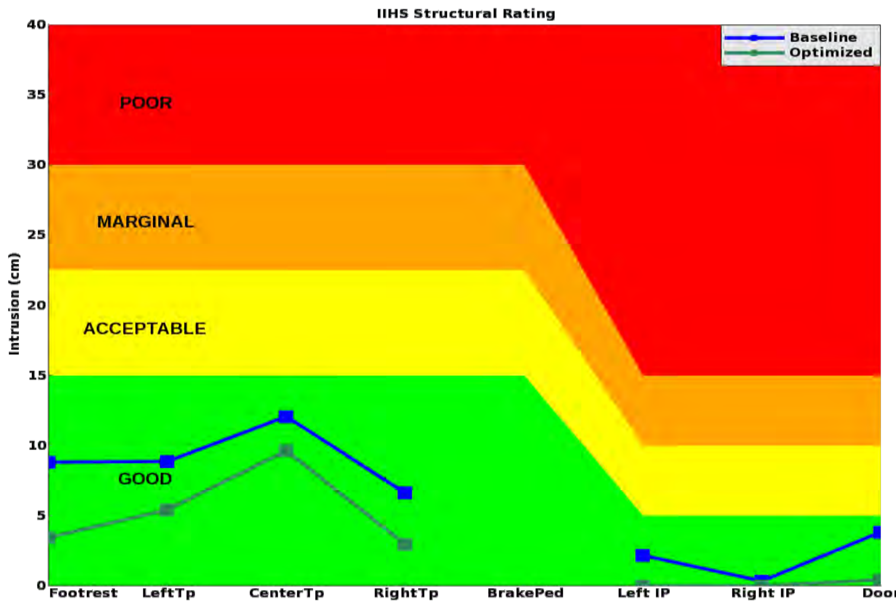



Figure 4.18-134: IIHS Frontal Dash Panel Intrusion Plot

The intrusion plot shows the optimized model has improved in terms of lower intrusion values and has achieved the better rating when compared to the baseline model for the critical dash panel locations.

A summary of IIHS performance measurements is provided in **Table 4.18-29** and **Table 4.18-30**.

**Table 4.18-29: Dash Intrusion Comparison Baseline vs. Optimized**

| No. | Frontal Crash Measurements | Baseline | Optimized |
|---|---|---|---|
| 1 | 1st Peak / Highest Peak | 6.23/50.3 | 6.98/45.2 |
| 2 | Time To Zero Velocity (ms) | 110.0 | 107.3 |
| 3 | Dynamic Crush Max. (mm) | 1317.2 | 1255.2 |

**Table 4.18-30: Dash Intrusion Comparison Baseline vs. Optimized**

| No. | Intrusion | Baseline (mm) | Optimized (mm) |
|---|---|---|---|
| 1 | Driver Footrest | 88.1 | 34.4 |
| 2 | Driver Toe Pan Left | 88.6 | 54.1 |
| 3 | Driver Toe Pan Center | 120.7 | 96.3 |
| 4 | Driver Toe Pan Right | 66.0 | 29.4 |
| 6 | Left IP | 21.6 | 0.0 |
| 7 | Right IP | 3.3 | 0.0 |
| 8 | Door Aperture | 38.3 | 4.3 |

From the intrusion values listed in **Table 4.17-30**, it is seen that intrusion pattern the baseline. The optimized model intrusions show an overall improvement in performance. Thus, based on the analysis of the baseline model, the optimized model with significant weight reduction meets the frontal offset impact performance requirements.

#### 4.18.5.3.2 FMVSS 214 - 38.5 mph MDB side impact

**Deformation Mode**

The deformation modes of the side impact optimized model and the baseline model are shown in **Figure 4.18-135** to **Figure 4.18-138**. It indicates both the baseline and the optimized models have similar deformation.

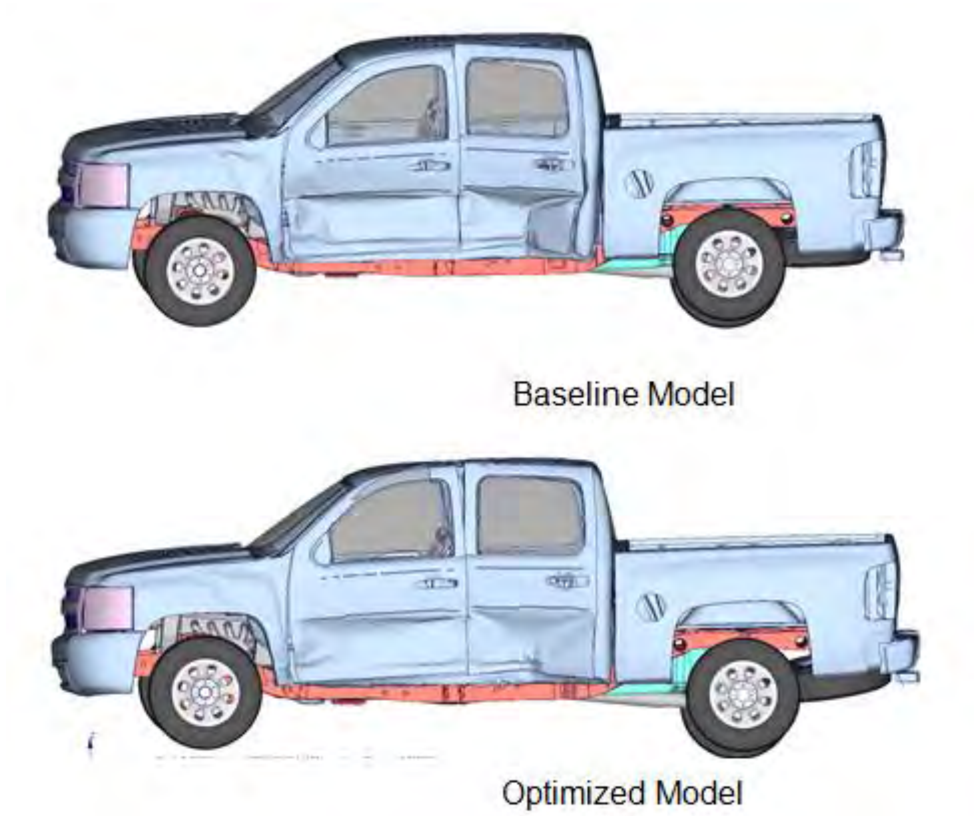



**Figure 4.18-135: Global Deformation Modes of Baseline and Optimized Models**

**Figure 4.18-136** shows front and rear door deformation modes at the impact area of B-pillar. It is observed the optimized model shows similar characteristics of deformation trend at the impact area. However the optimized model deformation is lower than baseline model.

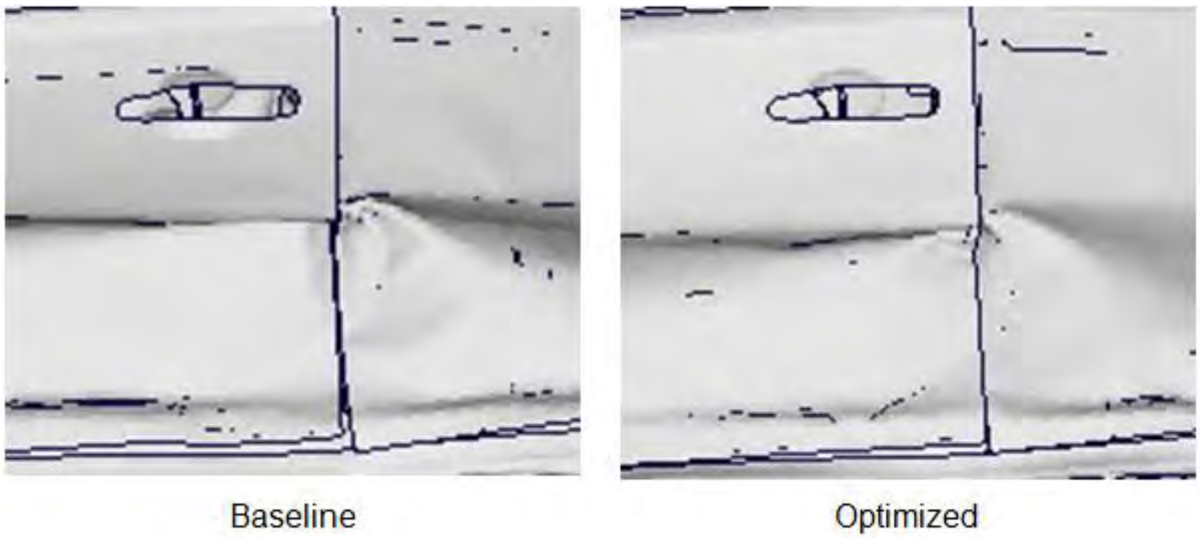



**Figure 4.18-136: Deformation Modes of Front and Rear Doors of Baseline and Optimized Models**

Similarly, **Figure 4.18-137** shows the same characteristics of rear door aperture area deformations for both the baseline and the optimized models. The optimized models less deformation compared to baseline model.


**Figure 4.18-137: Rear Door Aperture Deformations of Baseline and Optimized Models**

**Body Intrusion**

The key performance requirement of the side structure intrusion of the optimized model was compared with the baseline model. **Figure 4.18-138** shows the relative intrusion of the side structure in the optimized model at section1200Lwith respect to the un-deformed model. The sectional contour in green indicates the deformed shape of the optimized model with respect to the baseline sectional contour in blue. The sectional contour in gray color indicates the un-deformed shape.

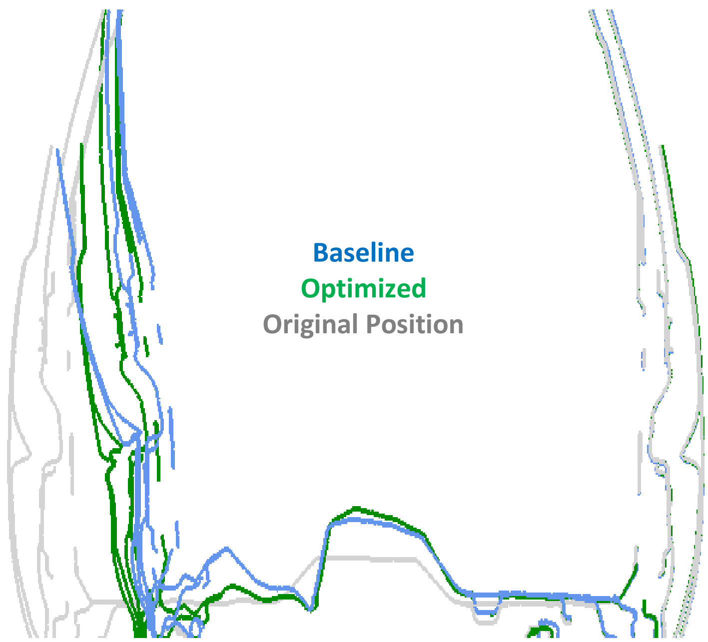



**Figure 4.18-138: FMVSS Side Intrusion Plot**

A summary of the relative intrusions of the B-pillar of the optimized model is shown in **Table 4.18-31**.

**Table 4.18-31: Baseline vs. Optimized Model - Relative Intrusions of Side Structure at 1200L for FMVSS 214 Side Impact**

| Measured Level | Baseline (mm) | Optimized (mm) |
|---|---|---|
| Level-5 | 22 | 12 |
| Level-4 | 169 | 173 |
| Level-3 | 289 | 242 |
| Level-2 | 335 | 267 |
| Level-1 | 321 | 281 |
| All measured points are taken at the vehicle exterior point | | |

From the above listed side structure intrusions, it is observed that the optimized model revealed lower intrusion at Level 3 to Level 1 and increased intrusion at Level 4 and 5. Therefore, the side structure intrusion performance of the optimized model is judged to be acceptable.

#### 4.18.5.3.3 IIHS - 31mph MDB Side Impact

**Deformation Mode**

The deformation modes of the side impact optimized model and the baseline model are shown in **Figure 4.18-139** through **Figure 4.18-141**. It indicates both the baseline and the optimized models have similar deformation shapes but different magnitude levels for intrusions.

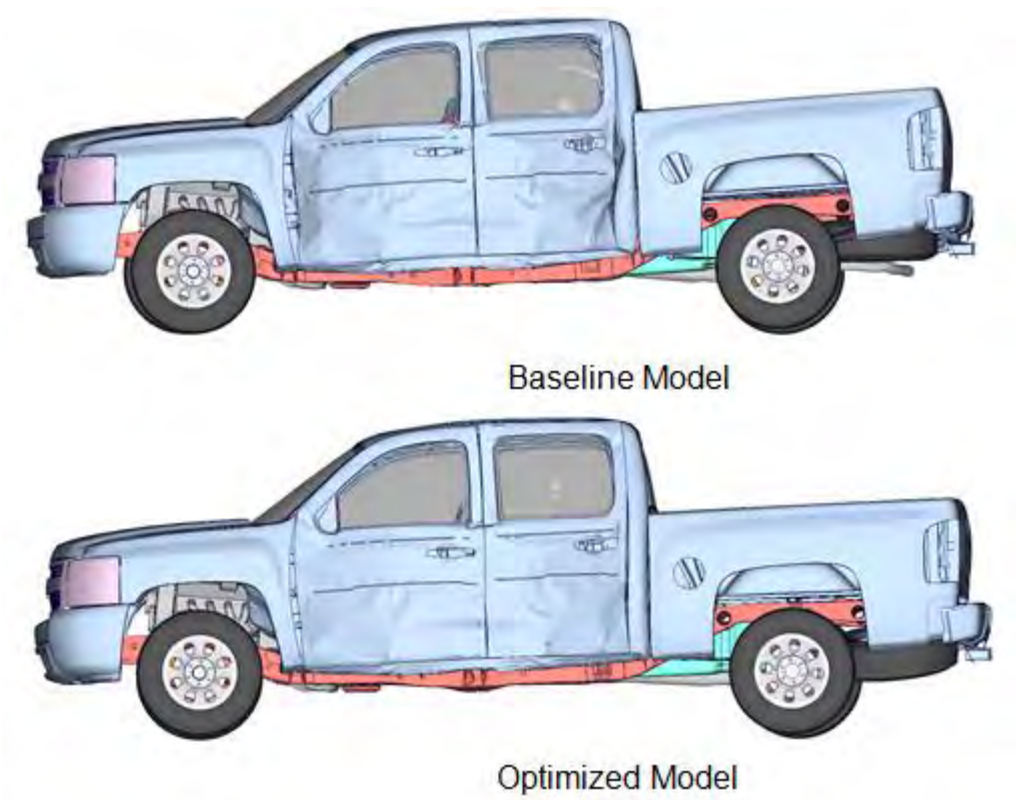



**Figure 4.18-139: Global Deformation Modes of Baseline and Optimized Models**

**Figure 4.18-140** shows front and rear door deformation modes at the impact area of B-pillar. It is observed the optimized model shows similar characteristics of deformation trend at the impact area. However the optimized model deformation is lower than baseline model.

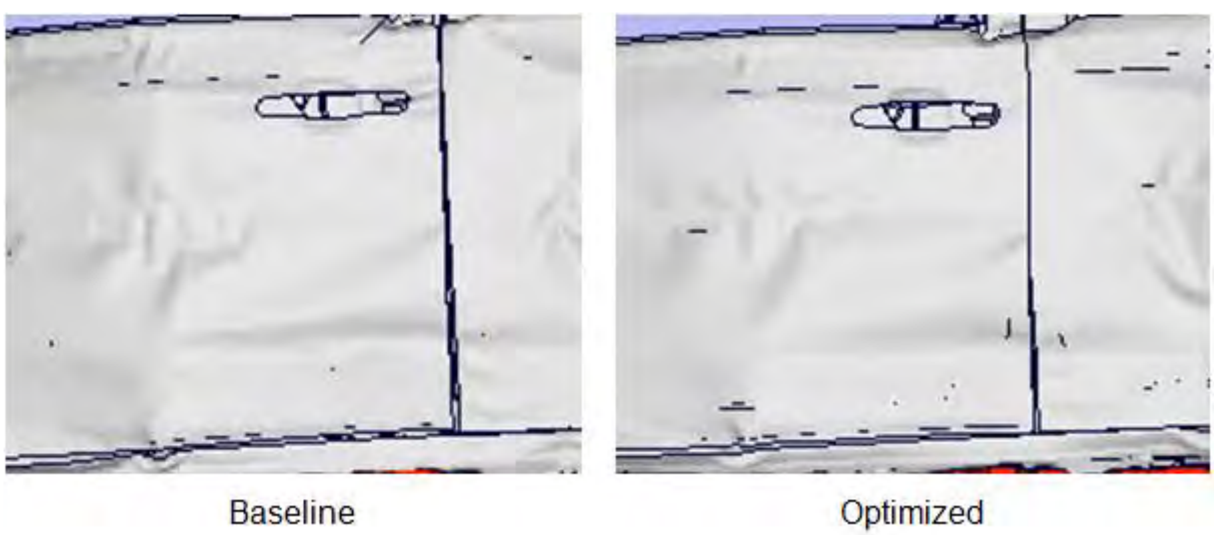



**Figure 4.18-140: Deformation Modes of Front and Rear Doors of Baseline and Optimized Models**

Similarly, **Figure 4.18-141** shows the same characteristics of rear door aperture area deformations for both the baseline and the optimized models. The optimized models less deformation compared to baseline model.

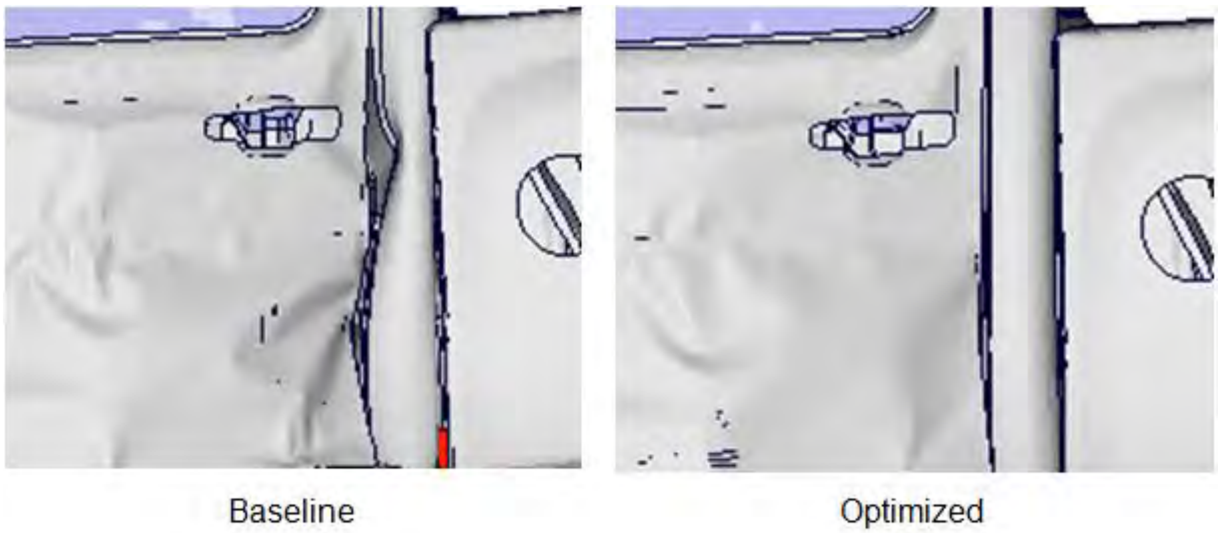



**Figure 4.18-141: Rear Door Aperture Deformations of Baseline and Optimized Models**

**Body Intrusion**

The key performance requirement of the side structure intrusion of the optimized model was compared with the baseline model. **Figure 4.18-142** shows the relative intrusion of the side structure in the optimized model at section 1200L with respect to the un-deformed model. The sectional contour in green indicates the deformed shape of the optimized model with respect to the baseline sectional contour in blue. The sectional contour in gray color indicates the un-deformed shape. The optimized model shows improvement over the baseline model in side structure intrusion levels.

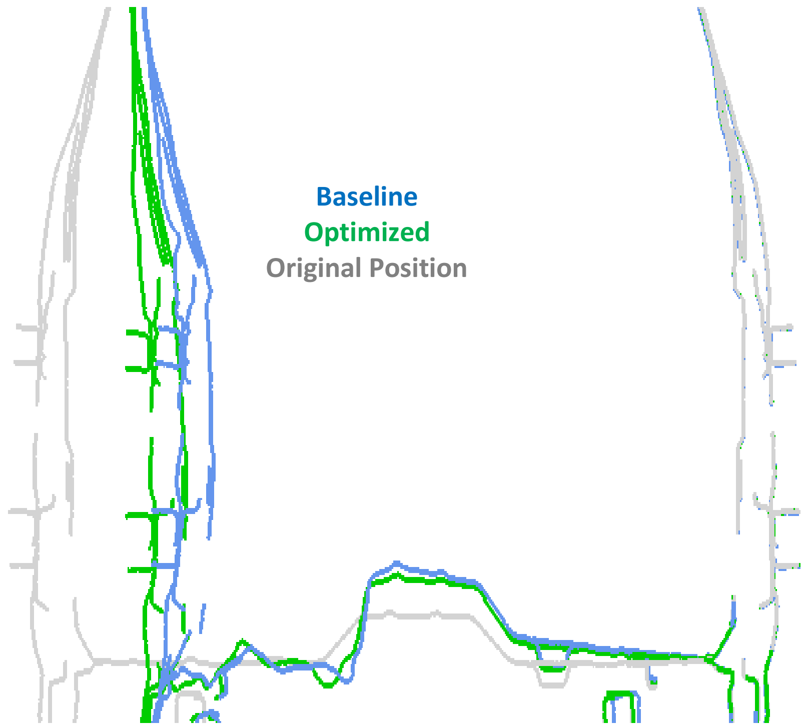



**Figure 4.18-142: IIHS Side Intrusion Plot**

**Table 4.18-32** is a summary of the relative intrusions of the optimized model B-pillar.

**Table 4.18-32: Baseline vs. Optimized Model - Relative Intrusions of Side Structure at 1200L for IIHS Side Impact**

| Measured Level | Baseline (mm) | Optimized (mm) |
|---|---|---|
| Level-7 | 166 | 118 |
| Level-6 | 299 | 224 |
| Level-5 | 334 | 254 |
| Level-4 | 351 | 277 |
| Level-3 | 345 | 279 |
| Level-2 | 333 | 276 |
| Level-1 | 310 | 263 |
| All measured points are taken at the vehicle interior point | | |

From the above listed side structure intrusions, it is observed that the optimized model revealed lower intrusion at all levels. Considering the worst case intrusion, the maximum side structure intrusions at 1200L section is less than the baseline results. Therefore the side structure intrusion performance of the optimized model is judged to be acceptable.

Additionally, for IIHS regulatory loadcases, the intrusions are compared from the occupant safety point of view. **Figure 4.18-143** shows the side structure intrusions of optimized and baseline models plotted with respect to the regulatory survival space contour measured from the seat center line.

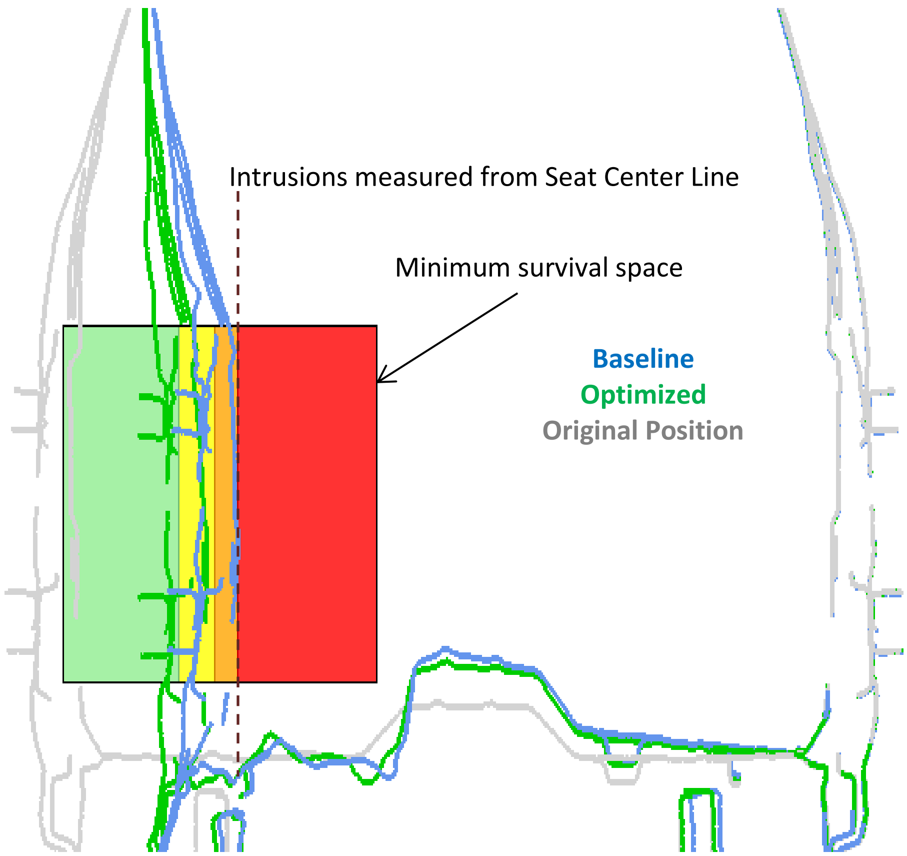
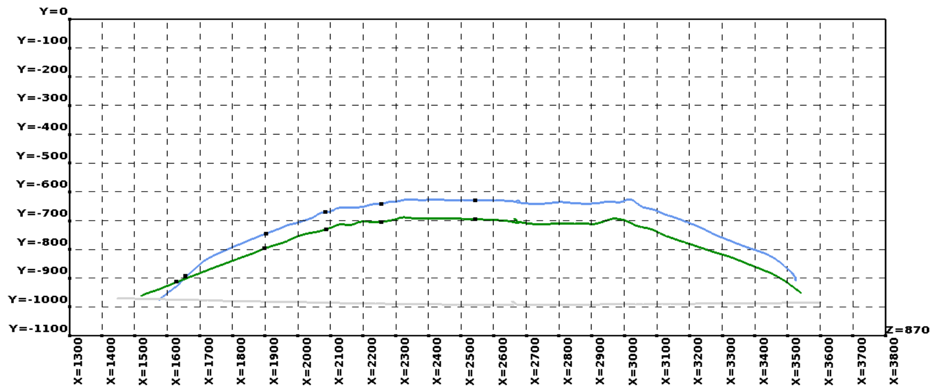



**Figure 4.18-143: Side Structure Intrusion Comparison with Survival Space Rate**

The survival space is rated using different zones based on the interior structure location at the end of the crash which are: good (green), acceptable (yellow), marginal (orange), and poor (red). From the above **Figure 4.18-143** the optimized model shows an acceptable rate whereas baseline model shows a marginal rate.

Similarly, the exterior crush of the side structure also is compared as shown in **Figure 4.18-144**. It is a sectional top view of the vehicle impact area representing the external crush tendency.




| Level | Baseline (mm) | Optimized (mm) |
|---|---|---|
| 1 | 82 | 62 |
| 2 | 236 | 186 |
| 3 | 315 | 254 |
| 4 | 347 | 284 |
| 5 | 363 | 296 |

**Figure 4.18-144: Side Structure Exterior Crush Comparison**

The green line shows the side crush tendency of the optimized model compared to the baseline tendency in blue line. The gray line shows the original un-deformed shape. The deformed shapes of the side structure were measured at the end of the simulation.

The intrusion numbers of the side structure deformations of the optimized model demonstrate a similar tendency and lower crush (table insert in **Figure 4.18-144**). Therefore the optimized with weight reduction meets the required baseline targets.

4.18.5.3.4 FMVSS 214—20 mph 5th Percentile Pole Side Impact

**Deformation Mode**

The deformation modes of the pole side impact optimized model and the baseline model are shown in **Figure 4.18-145** through **Figure 4.18-147**. It indicates both the baseline and the optimized models have similar deformation.

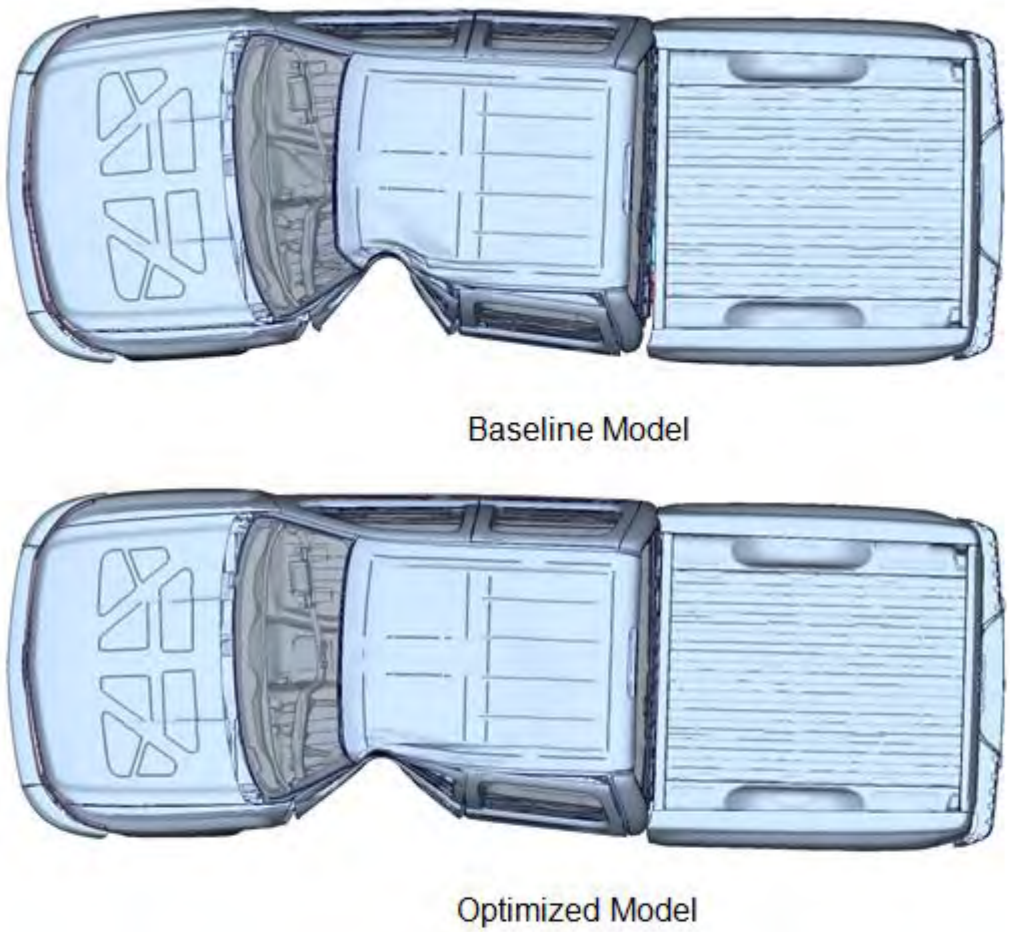



**Figure 4.18-145: Global Deformation Modes of Baseline and Optimized Models Top View at 200 ms**

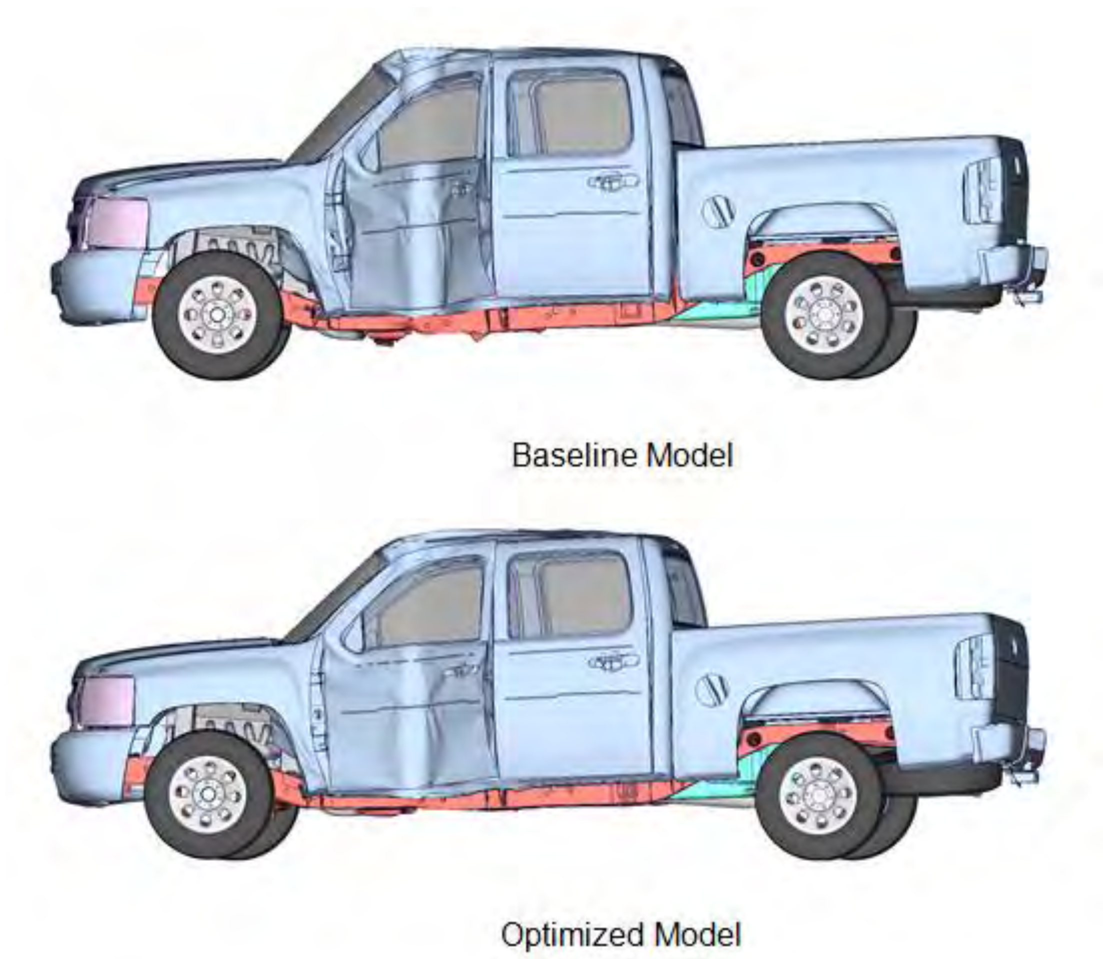



**Figure 4.18-146: Global Deformation Modes of Baseline and Optimized Models Side View at 200ms**

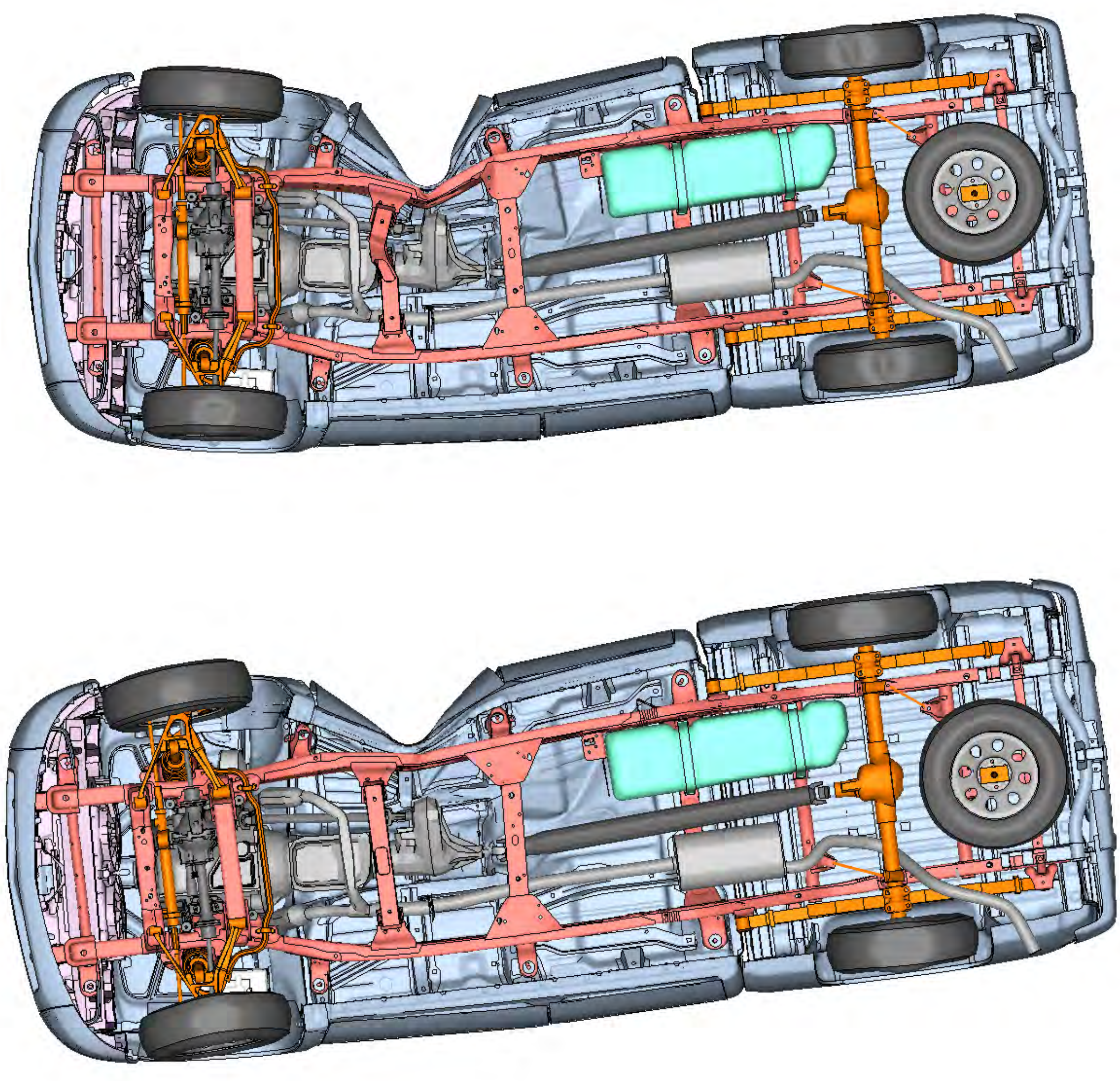


**Figure 4.18-147: Global Deformation Modes of Baseline (top) and Optimized (bottom) Models Bottom View at 200ms**

## Body Intrusion

The key performance requirement of the pole impact side structure intrusion of the optimized model was compared with the baseline model. **Figure 4.18-148** shows the relative intrusion of the side structure in the optimized model at section0L with respect to the un-deformed model. The sectional contour in green indicates the deformed shape of the optimized model with respect to the baseline sectional contour in blue. The sectional contour in gray color indicates the un-deformed shape. The optimized model shows improved performance compared to the baseline model in side structure intrusion levels.

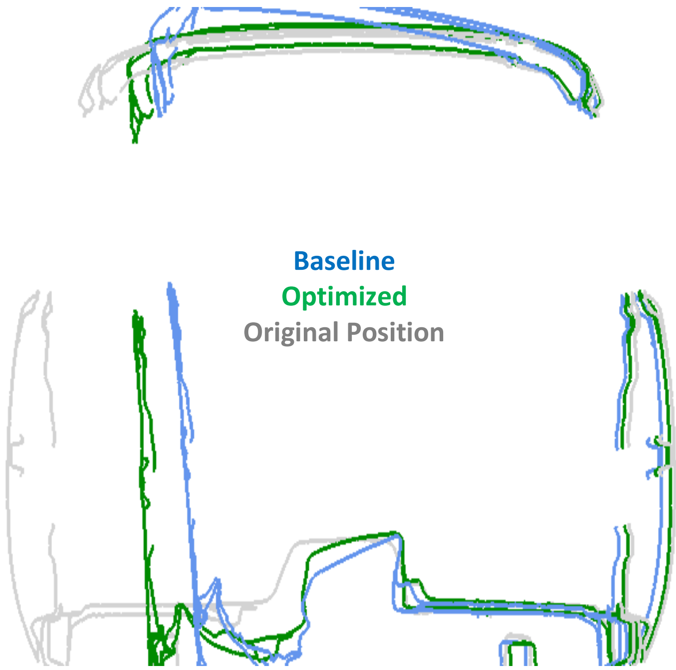



**Figure 4.18-148: Side Structure Intrusion Plot of Optimized Model at 0L Section**

A summary of the relative intrusions of the B-pillar of the optimized model is shown in **Table 4.18-33**.

**Table 4.18-33: Baseline vs. Optimized Model - Relative Intrusions of Side Structure @0L for Pole Side Impact**

| Measured Level | Baseline (mm) | Optimized (mm) |
|---|---|---|
| Level-5 | 241 | 157 |
| Level-4 | 492 | 366 |
| Level-3 | 546 | 410 |
| Level-2 | 553 | 417 |
| Level-1 | 510 | 360 |
| * All measured points are taken at the vehicle exterior point | | |

From the above listed side structure intrusions, it is observed that the optimized model revealed lower intrusion at all levels. As explained in **Section 4.18.2.1**, considering the worst case intrusion, the maximum side structure intrusions is less than the baseline results. Therefore, the pole impact side structure intrusion performance of the optimized model is judged to be acceptable.

#### 4.18.5.3.5 FMVSS 301—50 mph MDB Rear Impact

**Deformation Mode**

The deformation modes of the rear impact simulation of the optimized model are shown in **Figure 4.18-149** through **Figure 4.18-152**. Similar to the baseline model, these deformation modes indicate the rear structure protect the fuel tank system well during the crash event. In **Figure 4.18-150**, the rear door area shows no jamming shut of the door opening.

The skeleton view comparison of the optimized model rear inner structure deformation is shown in **Figure 4.18-150**. It shows a similar trend of the baseline model where the rear underbody was involved resulting in maximizing the crush energy absorption and minimizing the deformation of the rear door and fuel tank mounting areas.

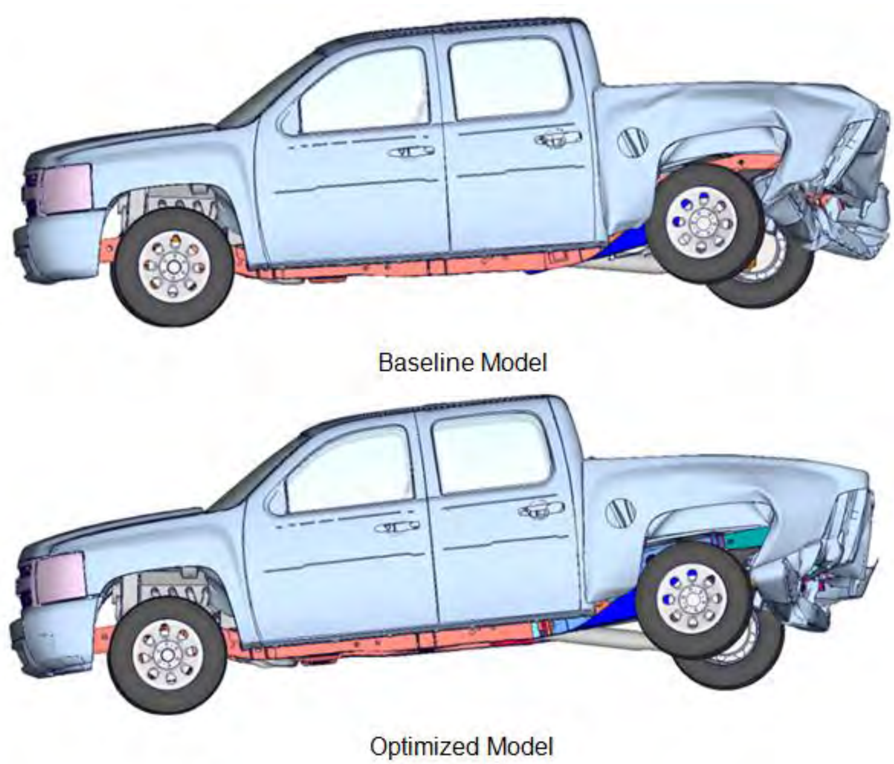



**Figure 4.18-149: Deformation Mode Comparison of Optimized Model - Left Side View at 120ms**

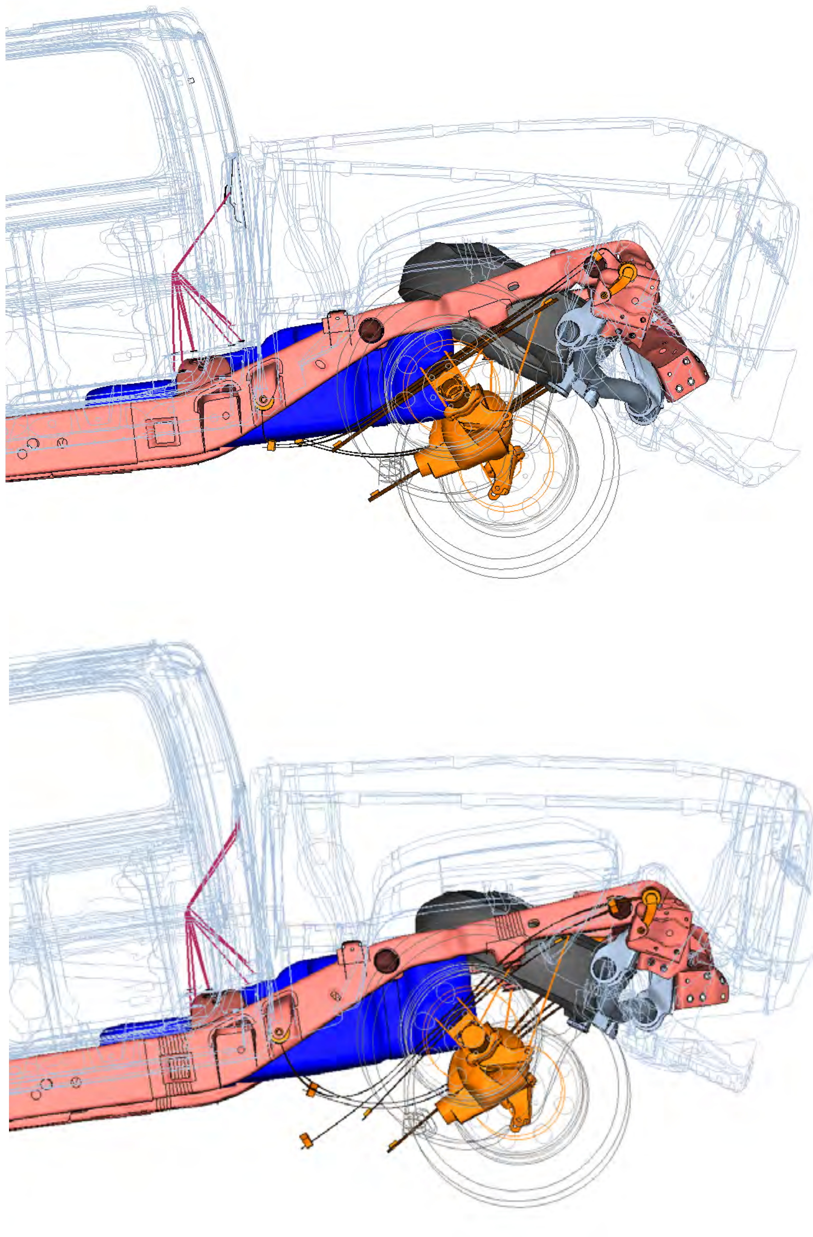


**Figure 4.18-150: Deformation Mode Comparison of Baseline (top) and Optimized (bottom) Model Rear Structure Area - Left Side Views at 120ms**

The bottom view of the rear underbody structure around the fuel tank area at the end of crash (120ms) is shown in **Figure 4.18-151** and **Figure** 4.18-152**.** This deformation mode shows the rear rail structure and the rear suspension mounting are also intact to protect the fuel tank system.

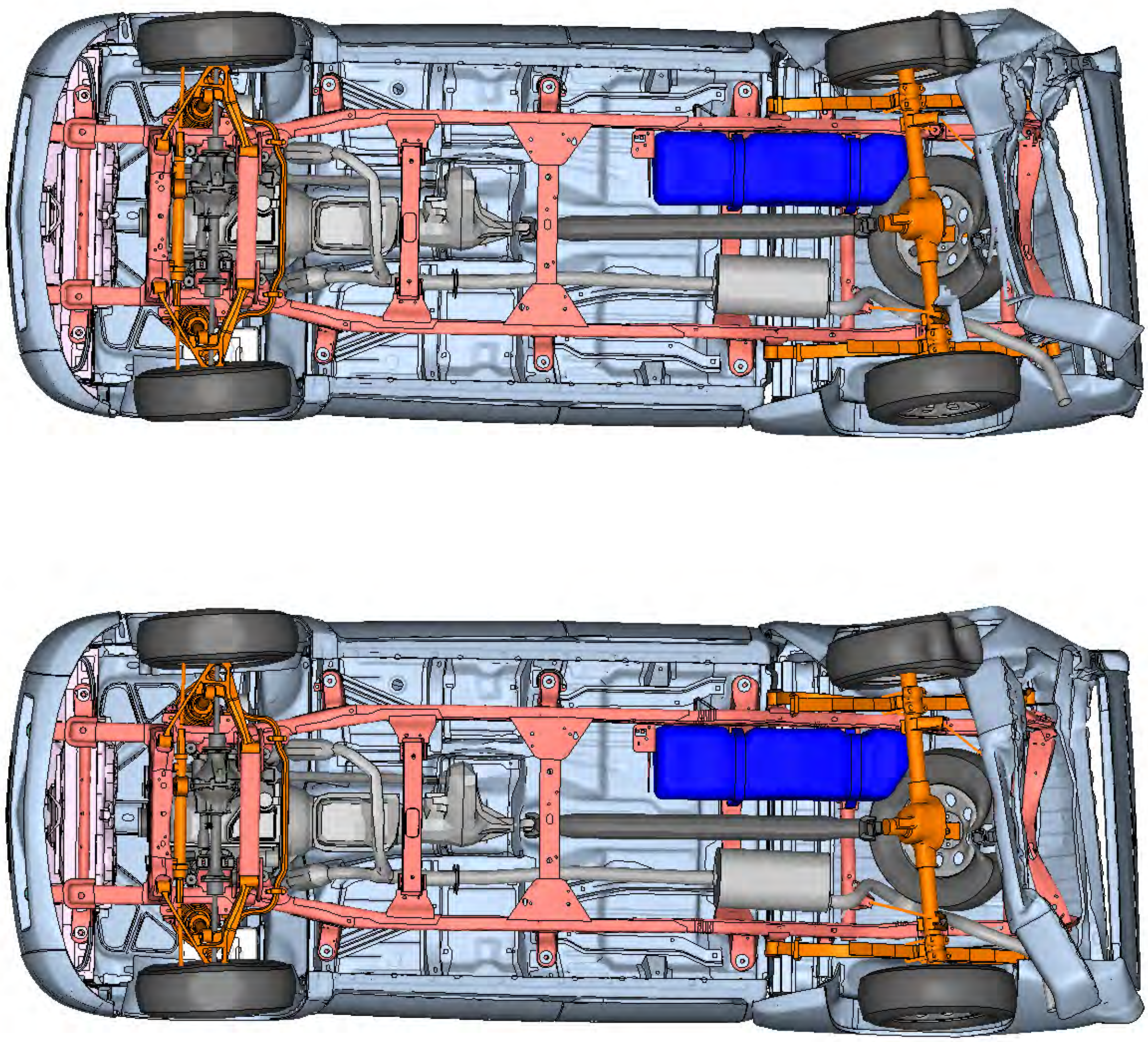


**Figure 4.18-151: Deformation Mode Comparison of Baseline (top) and Optimized (bottom) Model - Bottom Views at 120ms**

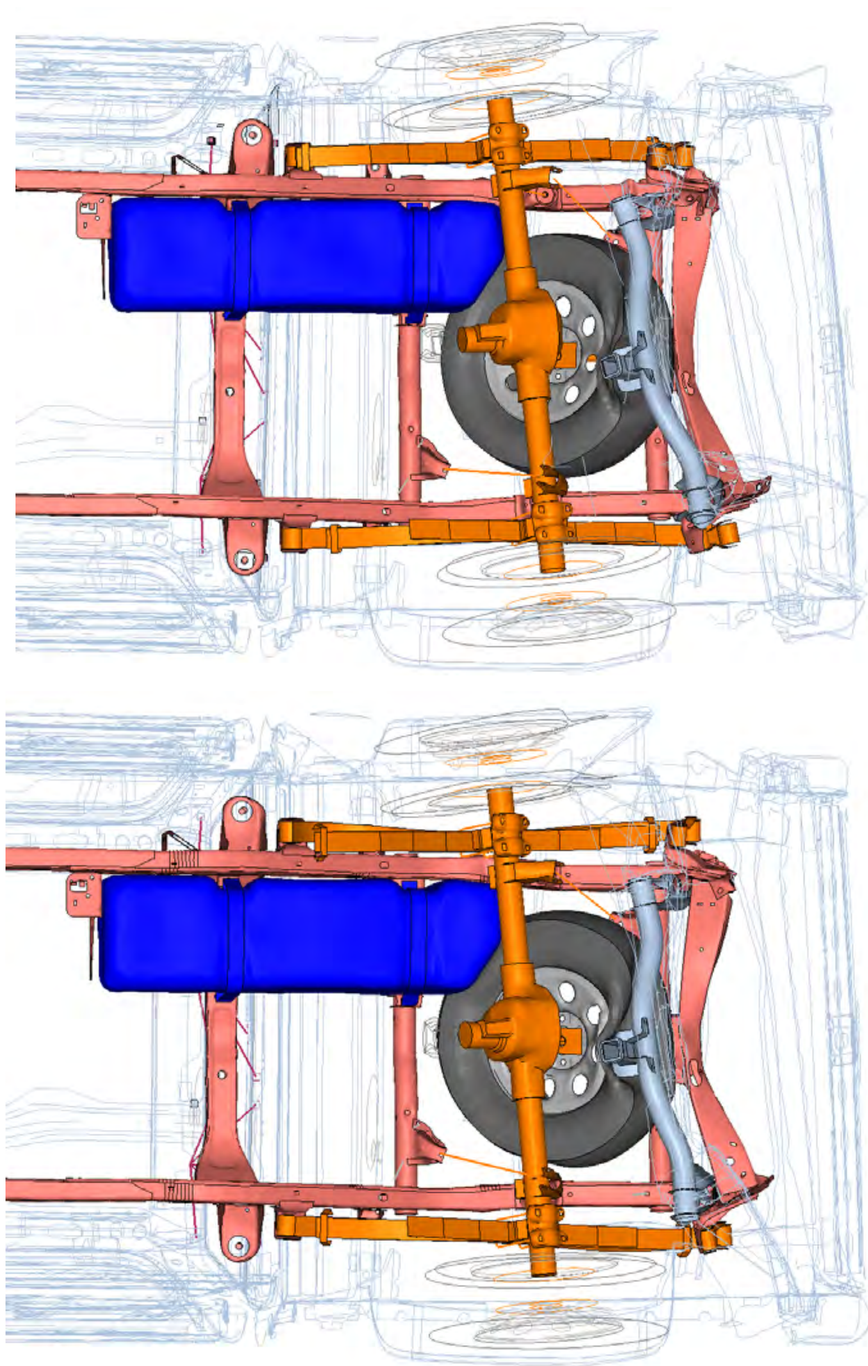


**Figure 4.18-152: Deformation Mode Comparison of Baseline (top) and Optimized (bottom) Rear Underbody Structure - Bottom Views at 120ms**

## Fuel Tank Deformation

The fuel tank integrity of the optimized model is further analyzed by its plastic strain plot and is compared to the baseline model. The fuel tank system strain plot was monitored as one of the necessary parameters in a rear impact scenario. **Figure 4.18-153** shows the comparison of the fuel tank system's strain plot after the crash.

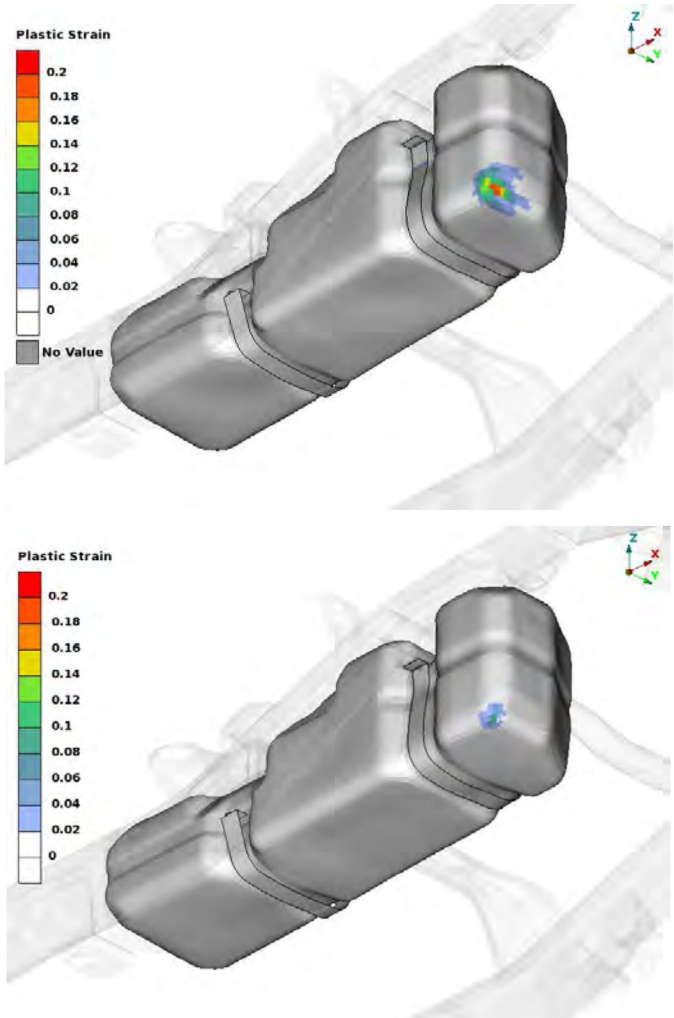



**Figure 4.18-153: Comparison of Fuel Tank System Integrity (Baseline, top; Optimized, bottom)**

Similar to the baseline model, the optimized model also indicates no significant risk of fuel system damage as the maximum strain is less than 10%, which is less than the expected plastic strain required to fail the tank material. It thus meets the baseline target in terms of fuel tank integrity.

**Structural deformation**

The rear impact structural performance of the optimized model is further compared with the baseline model in terms of zonal deformation and rear door opening area deformation (shown in **Figure 4.18-75**). The structural deformations measured at different zones are listed and compared to the baseline model in **Table 4.18-34**.

**Table 4.18-34: Rear Impact Structural Performance Comparison**

| Model | Under Structure Zone Deformation (mm) | | | | Door Opening (mm) | |
|---|---|---|---|---|---|---|
| | Zone-1 | Zone-2 | Zone-3 | Zone-4 (Max.) | Beltline | Dogleg |
| Baseline | 402.8 | 348.7 | 132.1 | 115.2 | 2.6 | -1.8 |
| Optimized | 448.7 | 355.5 | 125.8 | 130.9 | 0.1 | -0.3 |

Based on our acceptance criteria that the rear door must be capable of opening after the impact event and there must be fuel system integrity, the optimized model is judged acceptable.

#### 4.18.5.3.6 Roof Crush Resistance

**Deformation Mode**

The roof crush deformation mode at the final plot state is shown in **Figure 4.18-154**. It is noted that, similar to the baseline model, most of the deformation is concentrated on the roof rail, A-pillar, and B-pillar of the loaded side. The other neighboring structures remained un-deformed. The optimized model structure thus has the same level of roof crush resistance performance as the baseline model.

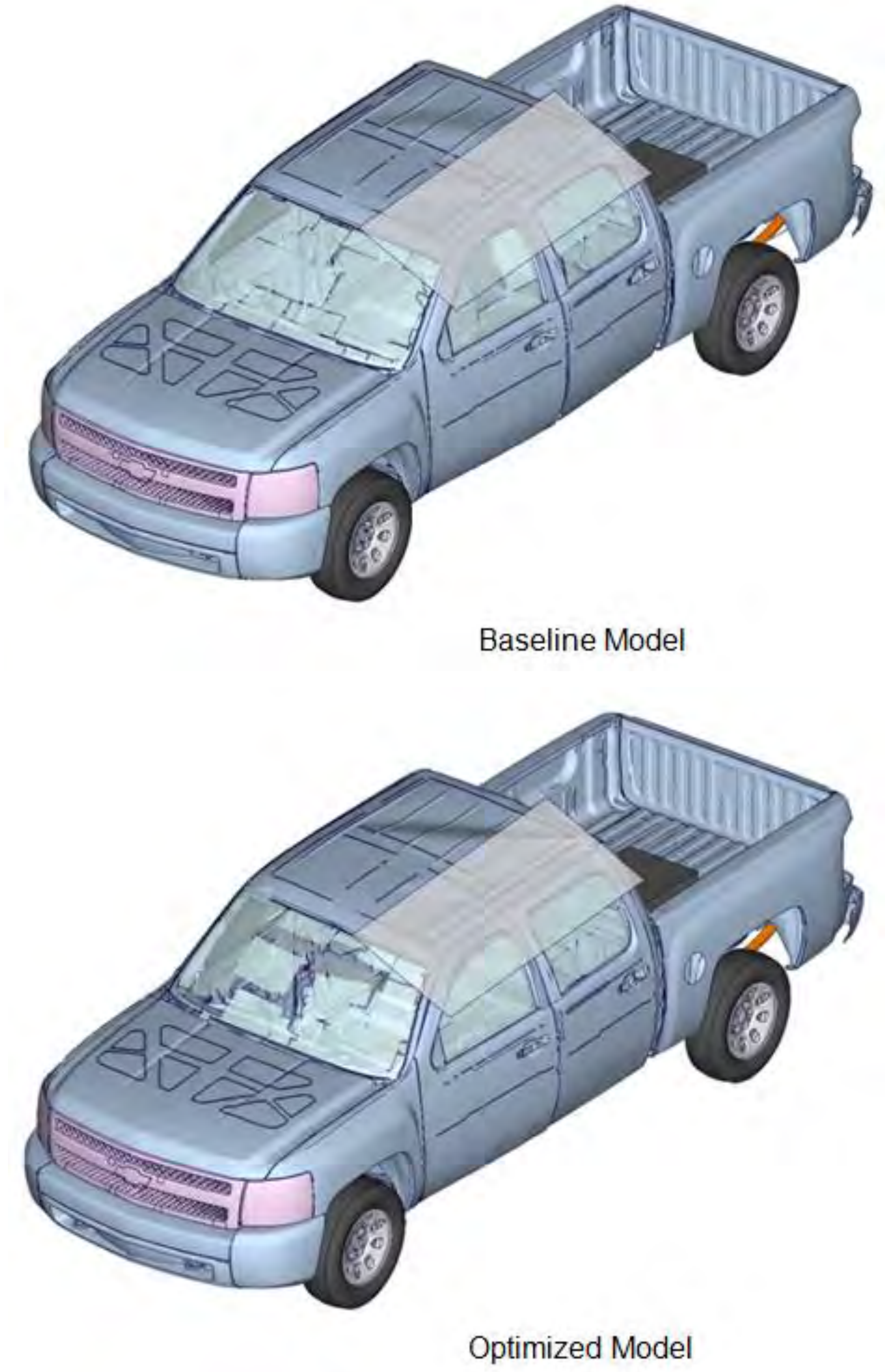



**Figure 4.18-154: Deformation Mode Comparison of Roof Crush**

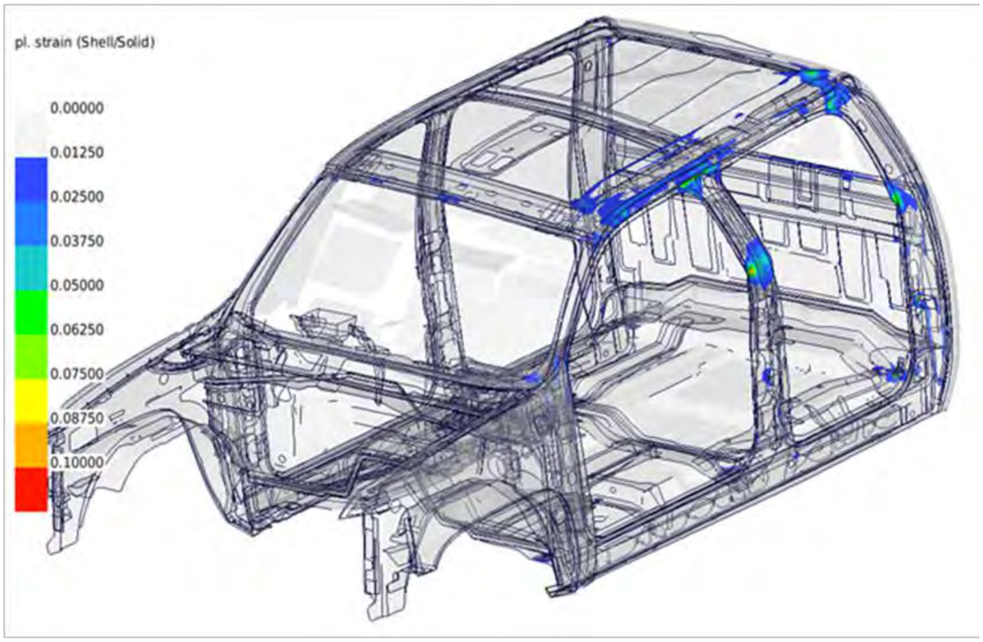



**Figure 4.18-155: Roof Crush Plastic Strain Areas ISO View at 100ms**

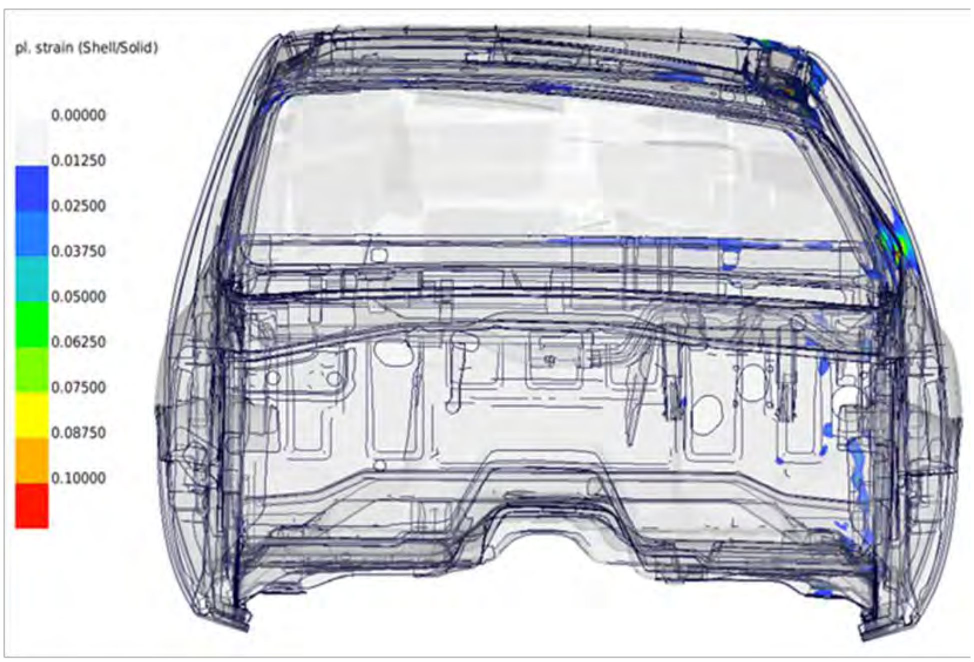



**Figure 4.18-156: Roof Crush Plastic Strain Areas Front View at 100ms**

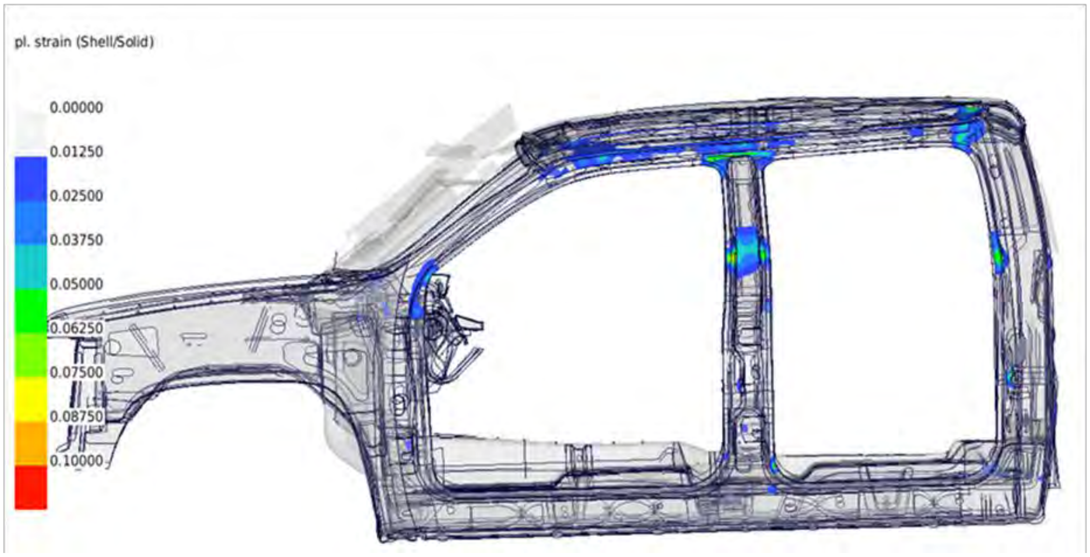



**Figure 4.18-157: Roof Crush Plastic Strain Areas Side View at 100ms**

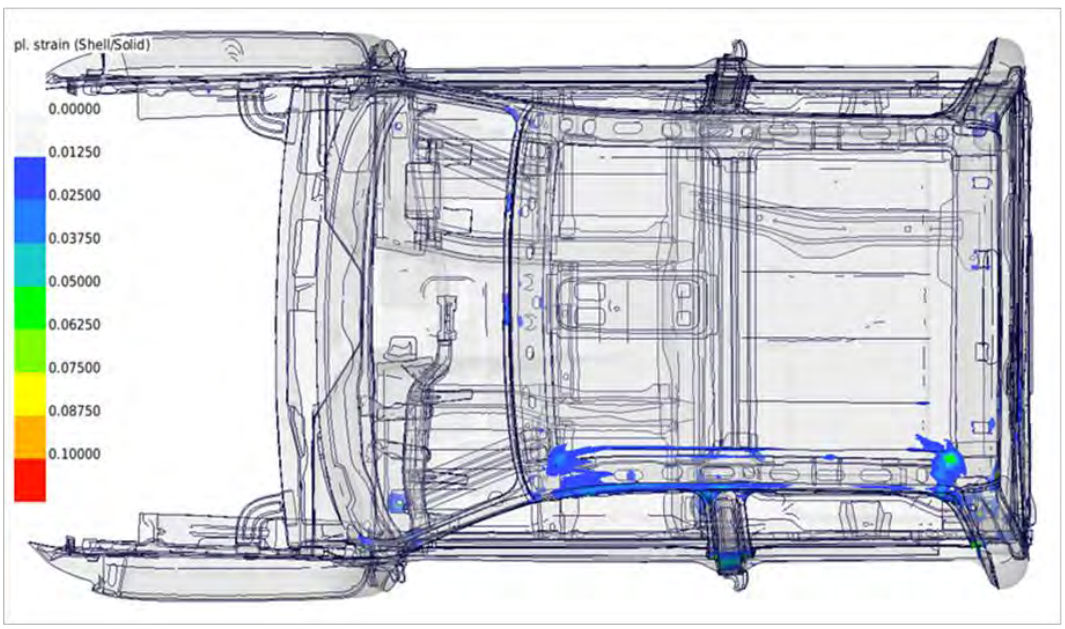



**Figure 4.18-158: Roof Crush Plastic Strain Areas Top View at 100ms**


**Figure 4.18-159: Roof Crush Load vs. Displacement Plot**

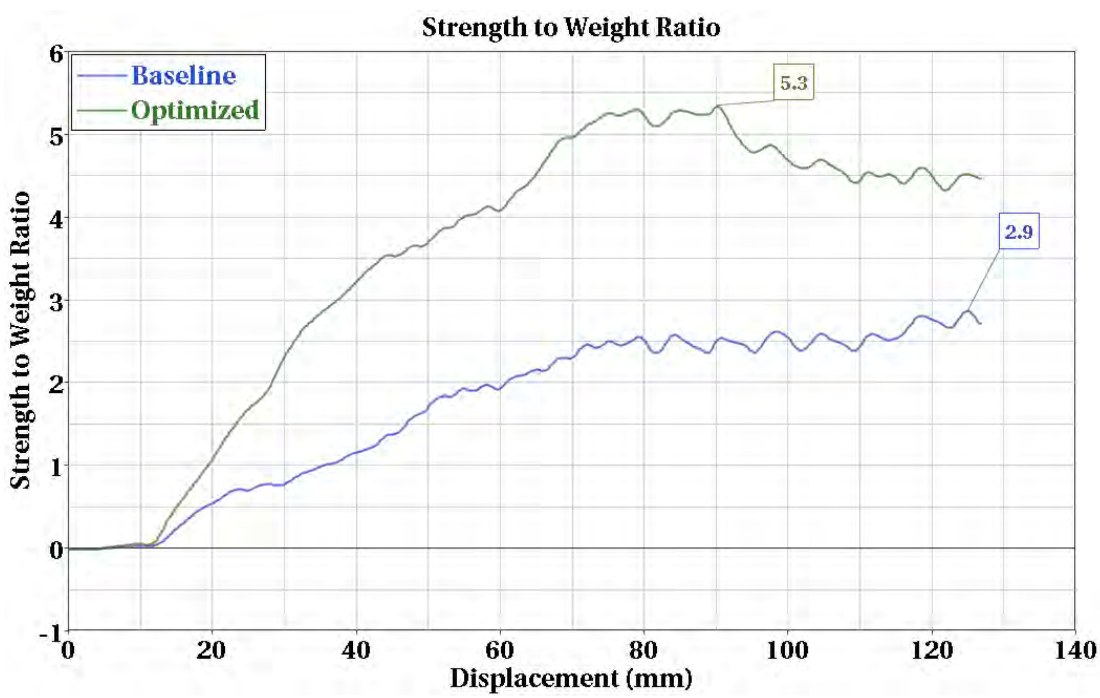



**Figure 4.18-160: Roof Strength to Weight Ratio Comparison**

Similar to the baseline model assessment, the curb weight of the optimized roof crush resistance model 1893 kg is used for roof strength calculation. It can be observed in **Figure 4.18-159**, **Figure 4.18-160**, and **Table 4.18-35** that the maximum load (98.5 kN) is greater than three times the curb weight force (55.3 kN) requirement within the platen displacement of 127 mm (this would classify as a "good" under the IIHS protocol).

A comparative summary of the optimized model's roof crush performance is provided in **Table 4.18-35**.

**Table 4.18-35: Rear Impact Structural Performance Comparison**

| Model | Curb Wt. (kg) | Peak Force (KN) | Strength to Weight Ratio |
|---|---|---|---|
| Baseline | 2454 | 69.3 | 2.9 |
| Optimized | 1893 | 98.5 | 5.3 |

#### 4.18.5.4 Closures Performance Results

Aluminum intensive closures have been analyzed for the same loadcases as detailed in Modular FEA Models. For the study a basic material and gauge study has been conducted utilizing the same geometry as the steel baseline door to give an indication of the mass reduction opportunity available.

For each closure analyzed the following data is presented:

- A thickness map for the sheet metal parts
- A material map (showing the material grades)
- A table comparing the performance to the baseline door for the loadcase matrix analyzed for the baseline door.

### 4.18.5.4.1 Front Door Performance

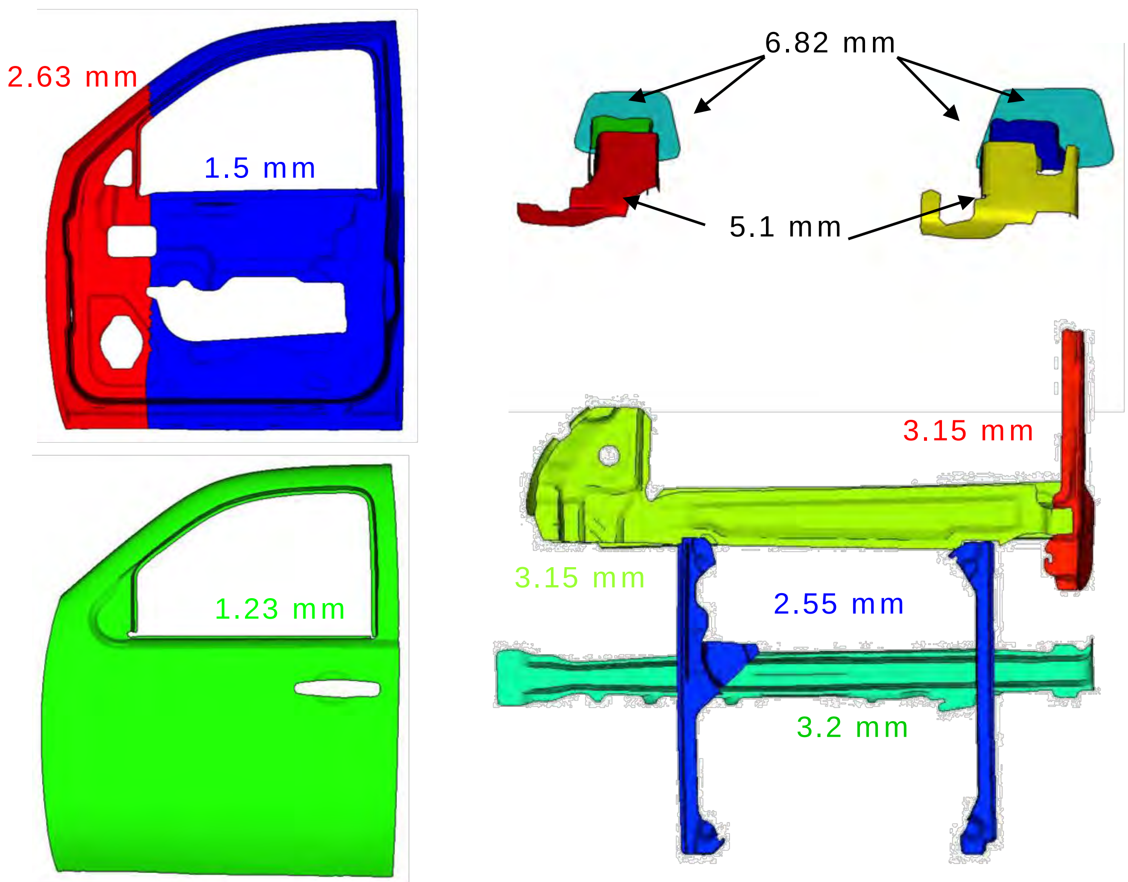



**Figure 4.18-161: Gauge Map of Optimized Front Door**

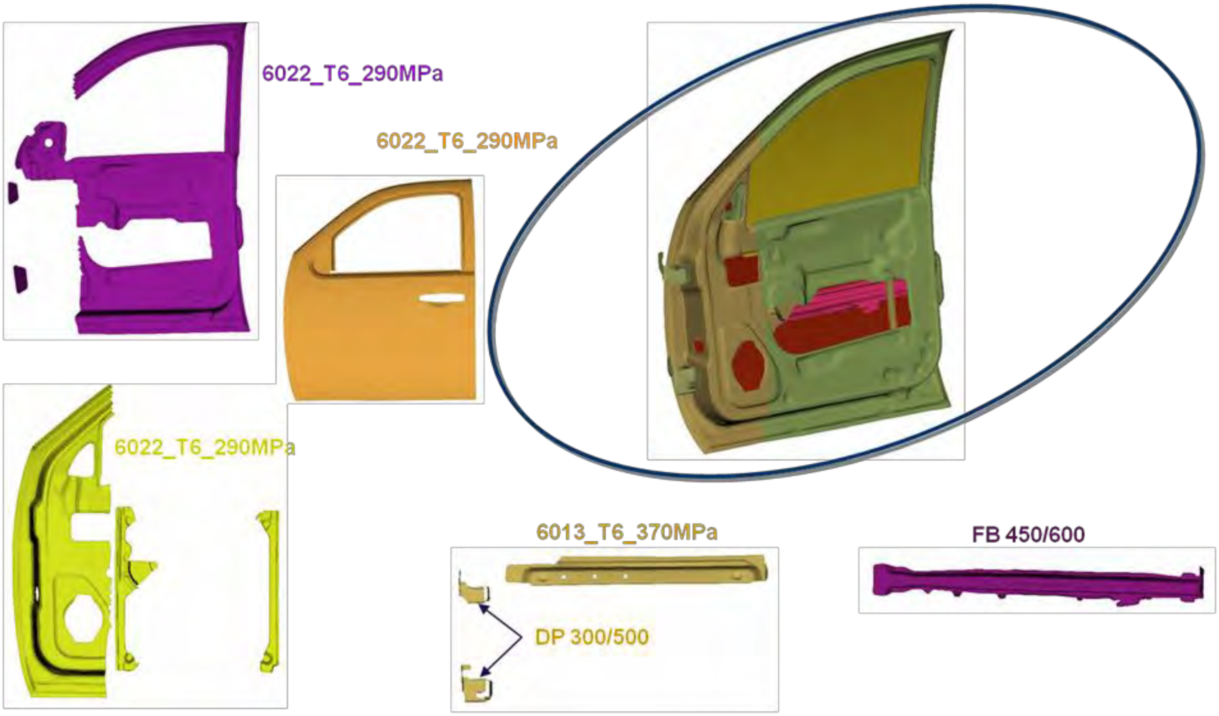



**Figure 4.18-162: Material Grade Map of Optimized Front Door**

**Table 4.18-36: Front Door Performance Results Optimized**

| No. | Loadcase | Baseline(mm) | Optimized(mm) |
|---|---|---|---|
| 1 | Frame Lateral Rigidity (Front) | no set | no Set |
| 2 | Frame Lateral Rigidity (Rear) | no set | no Set |
| 3 | Beltline Strength - Compression | 3.2 | 2.03 |
| 4 | Beltline Strength – Expansive | 0.94 | 1.3 |
| 5 | Torsional Rigidity | 2.98 | 3.36 |
| 6 | Door Sag | 0.62 set | 0.39 |
| 7 | Oil Canning Load Deflection | no set | no Set |

## 2) Rear Door Performance

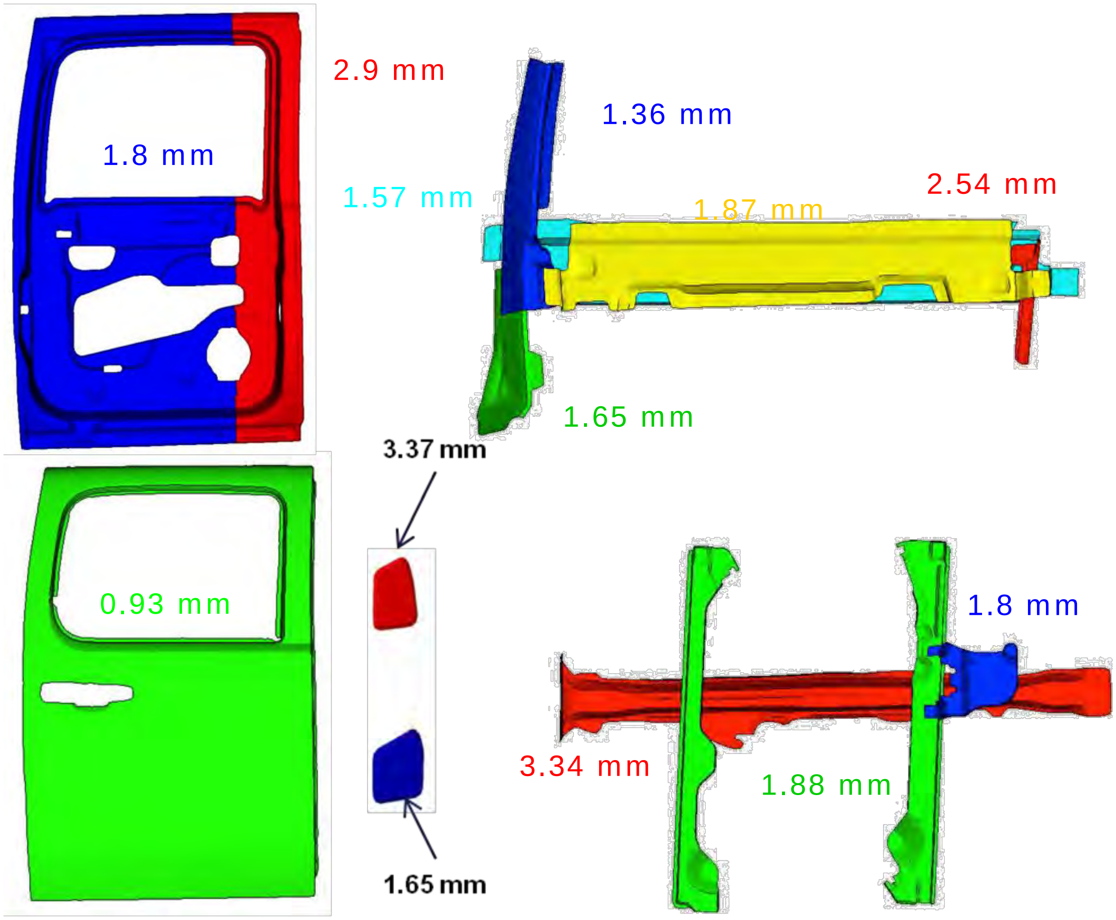



Figure 4.18-163: Gauge Map of Rear Door

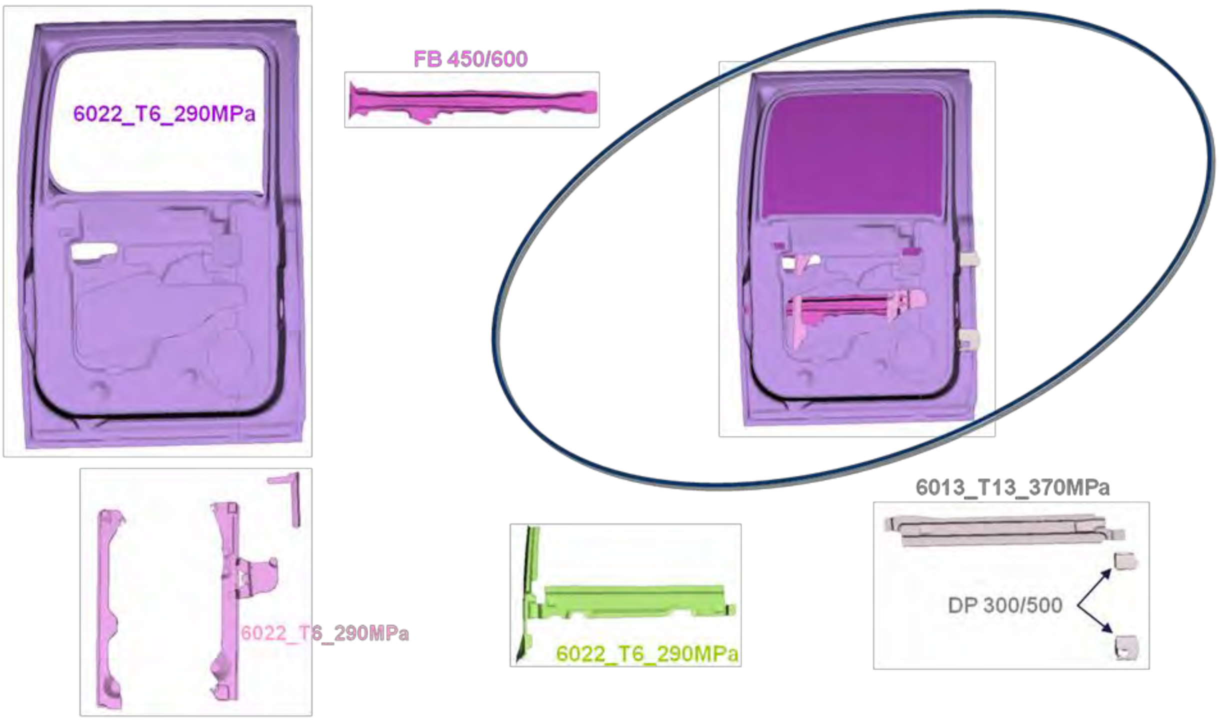



**Figure 4.18-164: Material Grade Map of Optimized Rear Door**

**Table 4.18-37: Rear Door Performance Results Optimized**

| No. | Loadcase | Baseline (mm) | Optimized (mm) |
|---|---|---|---|
| 1 | Frame Lateral Rigidity (Front) | No set | No Set |
| 2 | Frame Lateral Rigidity (Rear) | No set | No Set |
| 3 | Beltline Strength - Compression | 1.1 | 1.4 |
| 4 | Beltline Strength – Expansive | 1.0 | 1.35 |
| 5 | Torsional Rigidity | 3.8 | 3.8 |
| 6 | Door Sag | 0.5 set | 0.39 |
| 7 | Oil Canning Load Deflection | 0.025 | No Set |

### 3) Hood Performance

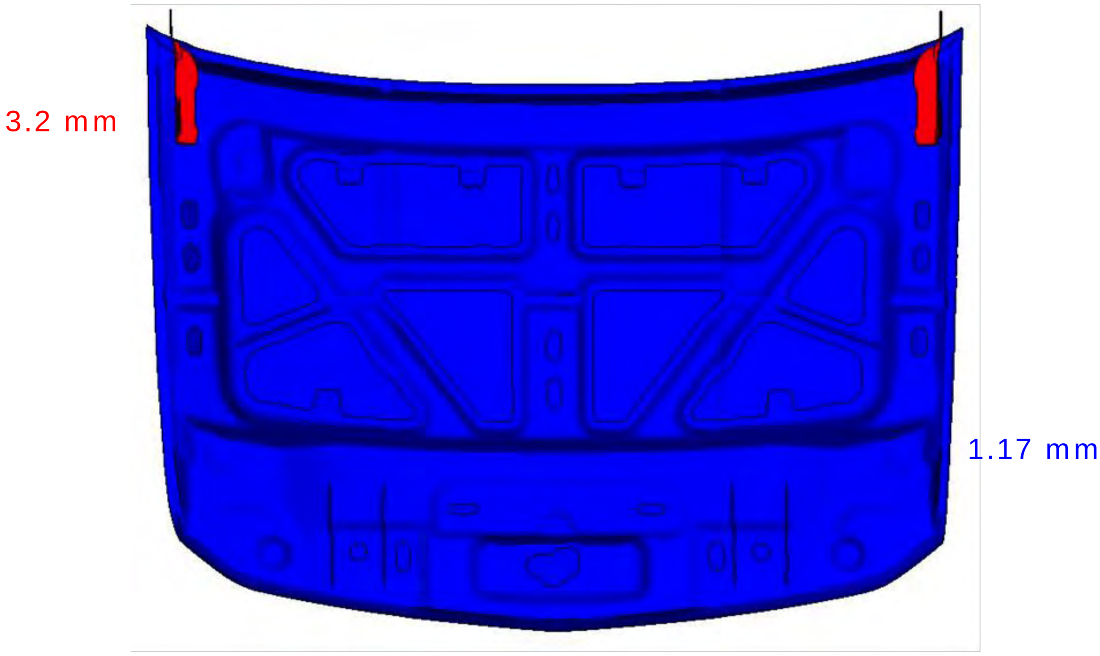



**Figure 4.18-165: Gauge Map of Optimized Hood**

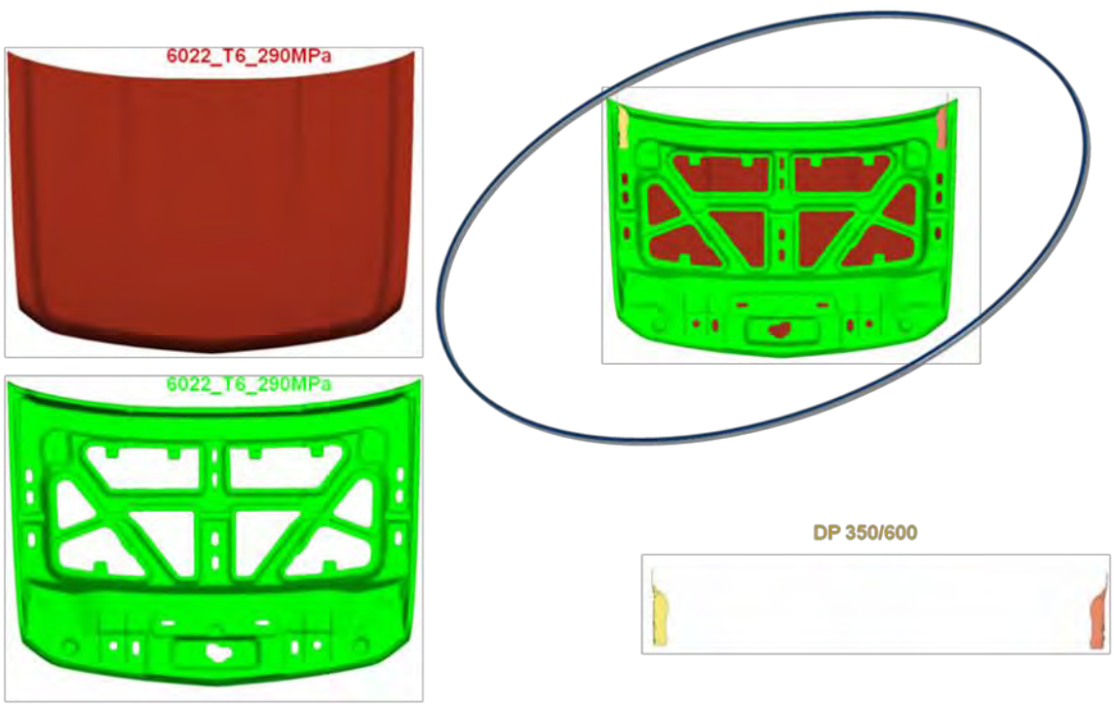



**Figure 4.18-166: Material Grade Map of Optimized Hood**

**Table 4.18-38: Hood Performance Results Optimized**

| No. | Loadcase | Baseline(mm) | Optimized (mm) |
|---|---|---|---|
| 1 | Cantilever Bending | 3.3E-03 | No Set |
| 2 | Torsional Rigidity | 8.83 | 13.4 |
| 3 | Oil Canning Load Deflection | no Set | no Set |

## 4) Tailgate Performance

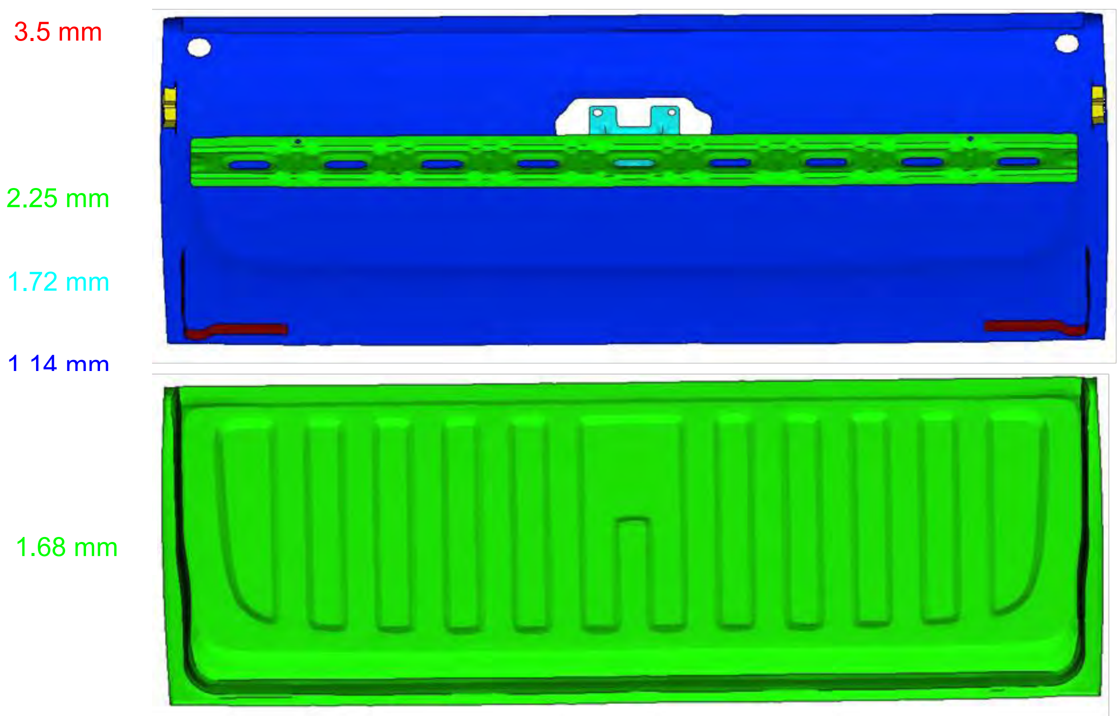



**Figure 4.18-167: Gauge Map of Optimized Tailgate**

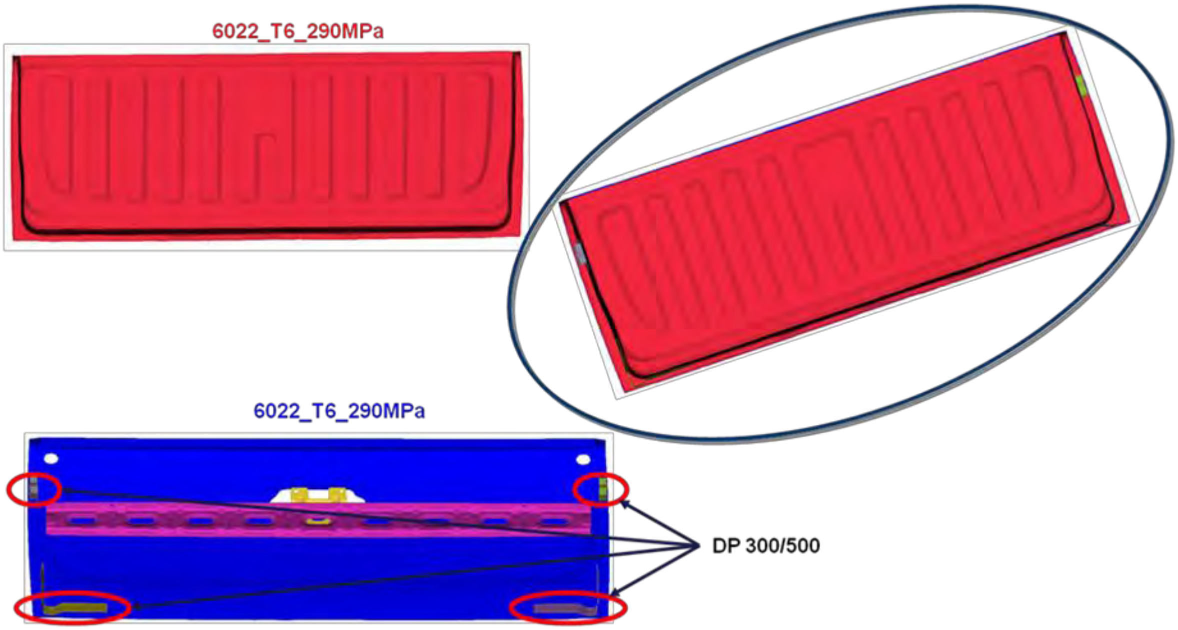



**Figure 4.18-168: Material Grade Map of Optimized Tailgate**

**Table 4.18-39: Tailgate Performance Results Optimized**

| No. | Loadcase | Baseline (mm) | Optimized (mm) |
|---|---|---|---|
| 1 | Torsional Rigidity | 0.44 | 0.62 |
| 2 | Oil Canning Load Deflection | 0.007 | No Set |

### 4.18.5.5 Bumper Impact Performance Results

The bumper system tests were not included in the optimization matrix for the project. The final optimized design has been analyzed for the FMVSS 581 loadcases and compared back to the baseline model. The model has been analyzed for both the baseline and the optimized configurations at the ride heights detailed in **Figure 4.18-169**.

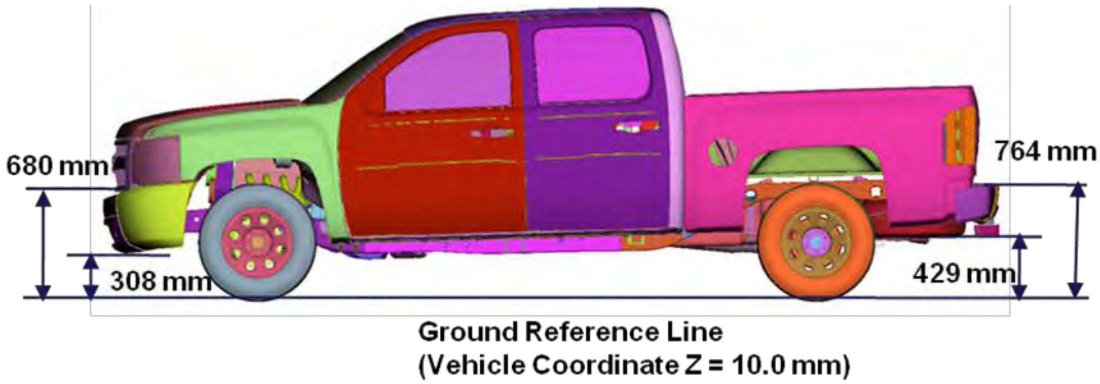



**Figure 4.18-169: Vehicle Height Dimension Baseline**

The performance is assessed against three criteria:

1. Minimum Gap pendulum to lamp/hood/box (target to maintain or increase versus the baseline)
2. Max plastic strain in the bumper beam
3. Max plastic strain in the crush can /tow bar (target to maintain or minimize versus the baseline <2%)

### Frontal Pendulum Impacts

The performance under FMVSS 581 loadcases for the front bumper baseline and optimized configurations are detailed in **Table 4.18-40** and **Table 4.18-41**. The performance versus the baseline is summarized below.

- The gap (pendulum– hood/lamps) is maintained (+/- 3mm)
- Maximum plastic strain in the aluminum bumper 12.6% (2.5mph rigid wall)
- Plastic strains in the crush cans are equivalent to the baseline (and less than 2%)

### Rear Pendulum Impacts

The performance under FMVSS 581 loadcases for the rear bumper baseline and optimized configurations are detailed in **Table 4.18-42** and **Table 4.18-43**. The performance versus the baseline is summarized as follows.

- The gap (pendulum – hood/lamps) is maintained (-1mm+15mm)
- Maximum plastic strain in the aluminum bumper 9.4% (2.5mph rigid wall)
- Plastic strains in the tow bar are equivalent to the baseline (and less than 2%)

**Table 4.18-40: Front Bumper Impact Performance Baseline**

| Baseline | | | | |
|---|---|---|---|---|
| Impact Scenario | Smallest Gap (mm) between Pendulum to lamp, hood when Fully Deformed | @ Time (ms) | Plastic Strain Bumper beam | Plastic Strain Crush Can |
| 16" Center Line 2.5 mph | 29.7 | 75 | 5.4 % | < 1% |
| 20" Center Line 2.5 mph | 24.2 | 45 | 6.4% | < 1% |
| 16" Offset Left 2.5 mph | 63.1 | 65 | 8.5% | < 1% |
| 20" Offset Left 2.5 mph | 51.3 | 50 | 8.1% | < 1% |
| 16" Corner Left 1.5 mph | 71.0 | 120 | 3.7% | < 1% |
| 20" Corner Left 1.5 mph | 68.2 | 70 | 3.1% | < 1% |
| Flat Rigid Wall 2.5 mph | 43.4 | 60 | 10.8% | < 1.8% |

**Table 4.18-41: Front Bumper Impact Performance Optimized**

| Optimized | | | | |
|---|---|---|---|---|
| Impact Scenario | Smallest Gap (mm) between Pendulum to lamp, hood when Fully Deformed | @ Time (ms) | Plastic Strain Bumper beam | Plastic Strain Crush Can |
| 16" Center Line 2.5 mph | 28.3 | 75 | 5.5 % | < 1% |
| 20" Center Line 2.5 mph | 22.2 | 45 | 6.6% | < 1% |
| 16" Offset Left 2.5 mph | 63.6 | 70 | 9.5% | < 1% |
| 20" Offset Left 2.5 mph | 48.9 | 55 | 8.7% | < 1% |
| 16" Corner Left 1.5 mph | 72.1 | 120 | 3.1% | < 1% |
| 20" Corner Left 1.5 mph | 66.5 | 70 | 4.6% | < 1% |
| Flat Rigid Wall 2.5 mph | 46.5 | 60 | 12.6% | < 1.9% |

**Table 4.18-42: Rear Bumper Impact Performance Baseline**

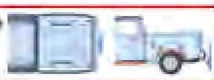
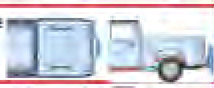
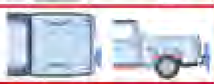
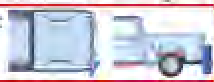
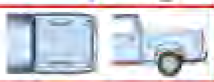
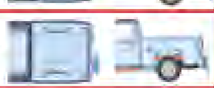
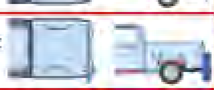
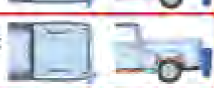
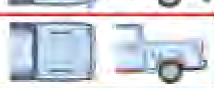
| Baseline | | | | |
|---|---|---|---|---|
| Impact Scenario | Smallest Gap (mm) between Pendulum to lamp, box when Fully Deformed | @ Time (ms) | Plastic Strain Bumper beam | Plastic Strain Trailer Hitch |
| 16" Center Line 2.5 mph  | 185.4 | 30 | 0% Plastic < 1% Steel | 1.15% |
| 20" Center Line 2.5 mph  | 105.4 | 45 | 0% Plastic < 1% Steel | 1.1% |
| 16" Offset Left 2.5 mph  | 88.1 | 50 | 16.8% Plastic 17.2% Steel | 0% |
| 20" Offset Left 2.5 mph  | 79.2 | 70 | 17.2% Plastic 20.8% Steel | 0% |
| 16" Corner Left 1.5 mph  | 60.0 | 90 | <1% Plastic 2.9% Steel | 0% |
| 20" Corner Left 1.5 mph  | 64.7 | 115 | <1% Plastic 2.9% Steel | 0% |
| Flat Rigid Wall 2.5 mph  | 100.3 | 40 | 8.2% Plastic 4.2% Steel | 0% |

**Table 4.18-43: Rear Bumper Impact Performance Optimized**

| Optimized | | | | |
|---|---|---|---|---|
| Impact Scenario | Smallest Gap (mm) between Pendulum to lamp, box when Fully Deformed | @ Time (ms) | Plastic Strain Bumper beam | Plastic Strain Trailer Hitch |
| 16" Center Line 2.5 mph  | 184.4 | 30 | 0% Plastic 0% Aluminum | <1% |
| 20" Center Line 2.5 mph  | 110.1 | 35 | 0% Plastic 0% Aluminum | <1% |
| 16" Offset Left 2.5 mph  | 95.0 | 50 | 17.2% Plastic 8.6% Aluminum | 0% |
| 20" Offset Left 2.5 mph  | 92.2 | 55 | 17.7% Plastic 9.4% Aluminum | 0% |
| 16" Corner Left 1.5 mph  | 74.0 | 70 | <1% Plastic 1.9% Aluminum | 0% |
| 20" Corner Left 1.5 mph  | 75.0 | 70 | <1% Plastic 1.9% Aluminum | 0% |
| Flat Rigid Wall 2.5 mph  | 106.1 | 35 | 7.6% Plastic 3.4% Aluminum | 1% |

#### 4.18.5.6 Vehicle Dynamics Performance Results

The light-weight design study also included investigation of vehicle dynamics performance of the light-weight vehicle. The vehicle dynamics performance of the optimized vehicle model was compared with that of the baseline model. Initially the full vehicle model of baseline vehicle dynamics was constructed in MSC ADAMS/Chassis by using the hard points data of the full vehicle, mass and inertia, spring damper characteristics and jounce and bumper rates.

The following outlines the basic steps taken to build vehicle dynamics models for baseline and optimized vehicle configurations.

- Build Baseline model and
- Correlate to Vehicle Data
  - Hard Point Data
  - Vehicle Mass and Inertia - VIMF
  - Kinematics and Compliance - K&C
  - Suspension Dampers (Force-Velocity Data)
  - Other Components
  - Weight Estimations
  - Occupant Cargo Positions
- Build Optimized Vehicle
- Vehicle Dynamic Performance Results Comparisons

  Static Vehicle Characteristics

  Dynamic Vehicle Characteristics

  Constant Radius

  J-Turn

  Frequency Response (2 Pass only)

  Static Stability Factor

**Summary of Results**

- The analysis above covered the following information:
- Match Optimized target values for

  Total axle mass and unsprung mass

  CG height at Curb

  Roll, pitch and yaw inertias

- Match Optimized to Baseline model for

  Ride height at GVW condition (typical "design" condition for trucks)

  Ride Frequency at GVW

  Roll Gradient

  Roll Couple Distribution (taking into account weight distribution difference)
- Evaluate at Various Loading Conditions

  1-Pass

  2-Pass

  5-Pass

  GVW (5-Pass + Cargo)

#### 4.18.5.6.1 Vehicle Dynamics Model Parameters

The following model parameters were included in the vehicle dynamics models (baseline and optimized configuration) accordingly by validating with physical Mass and Inertia (VIMF) and K&C tests.

**1) Hard Point Data**

The hard points are the structural joint locations of the front and rear suspensions on which vehicle sprung mass and unsprung mass are attached. The hard point data was measured by CMM (Co-ordinate Measuring Machine) techniques. **Table 4.18-44** and **Table 4.18-45**, respectively, show the summary of the hard point data of the front and rear suspensions.

**Table 4.18-44: Front Suspension Hard Points**

| Front Suspension (Curb) | Left | | |
|---|---|---|---|
| | X | Y | Z |
| UCA Front Bushing | -4809.8 | -480.5 | -187.2 |
| UCA Rear Bushing | -4533.9 | -482.3 | -229.2 |
| LCA Front Bushing | -4885.9 | -339.7 | -437.9 |
| LCA Rear Bushing | -4454.7 | -339.4 | -440.3 |
| Lower Ball Joint | -4631.2 | -783 | -468.5 |
| Upper Ball Joint | -4609.5 | -727.3 | -203.2 |
| Wheel Center | -4624 | -865.1 | -371.8 |
| Tire Patch | -4624 | -865.1 | -737.8 |
| Spindle Alignment Point | -4624 | -864.1 | -371.8 |
| Outer Tie Rod Ball | -4787.4 | -802.8 | -358.3 |
| Inner Tie Rod Ball | -4788.4 | -395.3 | -347.4 |
| Lower Shock | -4672.7 | -598.7 | -404.6 |
| Upper Shock | -4672.1 | -491.6 | -17 |
| Spring Lower | -4672.2 | -566.2 | -287 |
| Spring Upper | -2671.3 | -504.9 | -65.2 |

**Table 4.18-45: Rear Suspension Hard Points**

| Rear Suspension (Curb) | Left | | | Right | | |
|---|---|---|---|---|---|---|
| | X | Y | Z | X | Y | Z |
| Leaf Spring to Axle | -981.7 | -655.4 | -309.4 | | | |
| Leaf Spring to Frame | -1794.8 | -622.9 | -334.3 | | | |
| Leaf Spring to Shackle | -193.9 | -626.2 | -148.8 | | | |
| Shackle to Frame | -191.9 | -626.4 | -260.1 | | | |
| Wheel Center | -971.9 | -847.7 | -436.6 | | | |
| Shock Lower | -872.1 | -483.0 | -551.5 | -1065.3 | 490.5 | -559.6 |
| Shock Upper | -691.7 | -375.0 | -71.1 | -1283.7 | 371.1 | -77.7 |
| bumper align | -981.8 | -505.4 | -245.0 | | | |
| bumper tip | -981.0 | -503.6 | -319.2 | | | |
| contact point | -979.9 | -501.6 | -385.5 | | | |

## 2) Mass and Inertia (VIMF) Data

Vehicles mass and inertia were measured at Ford Motor Company VIMF (Vehicle Inertia Measuring Facility).

**Table** 4.18-46 shows the VIMF data of the full vehicle.

**Table 4.18-46: Mass and Inertia Baseline Model**

| Configuration: 4x4, Crew Cab, 5.3L<br>Condition: Curb | | Left (kg) | Right (kg) | Total (kg) | CG Height (mm) | Pitch Inertia (kg-m^2) | Yaw Inertia (kg-m^2) | Roll Inertia (kg-m^2) |
|---|---|---|---|---|---|---|---|---|
| Baseline Target (VIMF Measured) | Front Axle | 733.50 | 710.30 | 1443.80 | 718.6 | 6381 | 6781 | 1090 |
| | Rear Axle | 522.20 | 519.40 | 1041.60 | | | | |
| | | | | 2485.40 | | | | |

The physical weights of the left and right of front and rear of the vehicle respectively are listed. Center of Gravity (CG) height was measured as necessary parameter to build the ADAMS/Chassis model. The X co-ordinates front and rear suspensions CG, were measured at the axis of front and rear axles. Assuming the model symmetry, the Y co-ordinates of front and rear suspension CG was taken as 0.

## 3) Kinematics and Compliance (K&C) Data

Kinematics and Compliance test was conducted on the baseline vehicle at Ford Motor Company K&C laboratory. The vehicle motion characteristics, suspension dimensional ranges were recorded accordingly for correlation purpose. **Table 4.18-47** shows a summary of K&C test of baseline vehicle.

**Table 4.18-47: K&C Test Summary Baseline Model**

| | | Left Front | Right Front | Front | Left Rear | Right Rear | Rear |
|---|---|---|---|---|---|---|---|
| Vertical Motion Test - engine not running / anti-roll bars connected (Full Suspension Travel) | | | | | | | |
| 1 bump steer | deg/m | -7.4278 | 10.6986 | | -0.24976 | -0.13398 | |
| 2 bump camber | deg/m | -15.125 | -16.7041 | | -1.5771 | -1.6128 | |
| 3 bump spin | deg/m | 32.2636 | 31.9273 | | -3.7763 | -3.9238 | |
| 4 lateral wheel centre compliance | mm/mm | -0.03821 | 0.03291 | | -0.00426 | 0.00113 | |
| 5 lateral tire contact patch compliance | mm/mm | -0.11686 | 0.12108 | | -0.00592 | 0.00346 | |
| 6 longitudinal wheel centre compliance | mm/mm | 0.04875 | 0.06187 | | 0.01975 | 0.0192 | |
| 7 longitudinal tire contact patch compliance | mm/mm | -0.14227 | -0.13576 | | 0.04438 | 0.03969 | |
| 8 suspension rate | N/mm | 46.035 | 46.6785 | | 37.9017 | 37.6159 | |
| 9 ride rate | N/mm | 39.3942 | 39.7922 | | 33.8601 | 33.5955 | |
| 10 tire radial rate | N/mm | 273.191 | 273.006 | | 309.222 | 314.29 | |

## 4) Suspension Dampers (Force-Velocity) Data

The front and rear suspension dampers characteristics were measured at Tenneco Automotive Roehrig EMA damper dynamometer testing lab. **Figure 4.18-170** and

**Figure 4.18-171** show the front and rear suspension damper characteristics in terms of force-velocity curves used in the baseline model.

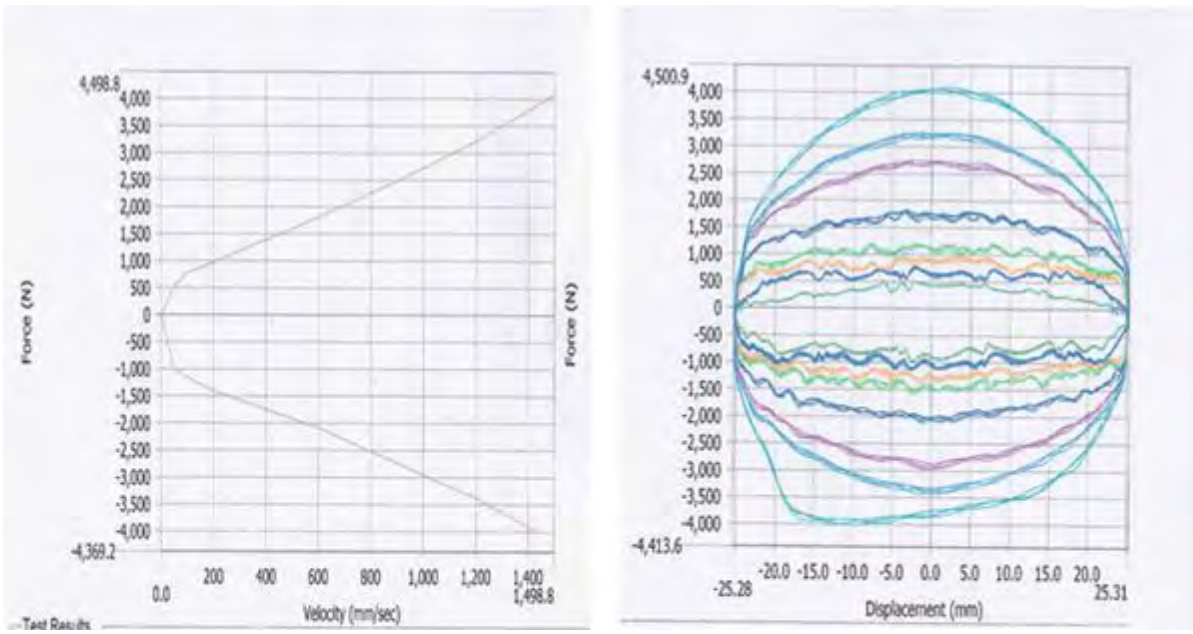



**Figure 4.18-170: Front Suspension Damper Characteristics**

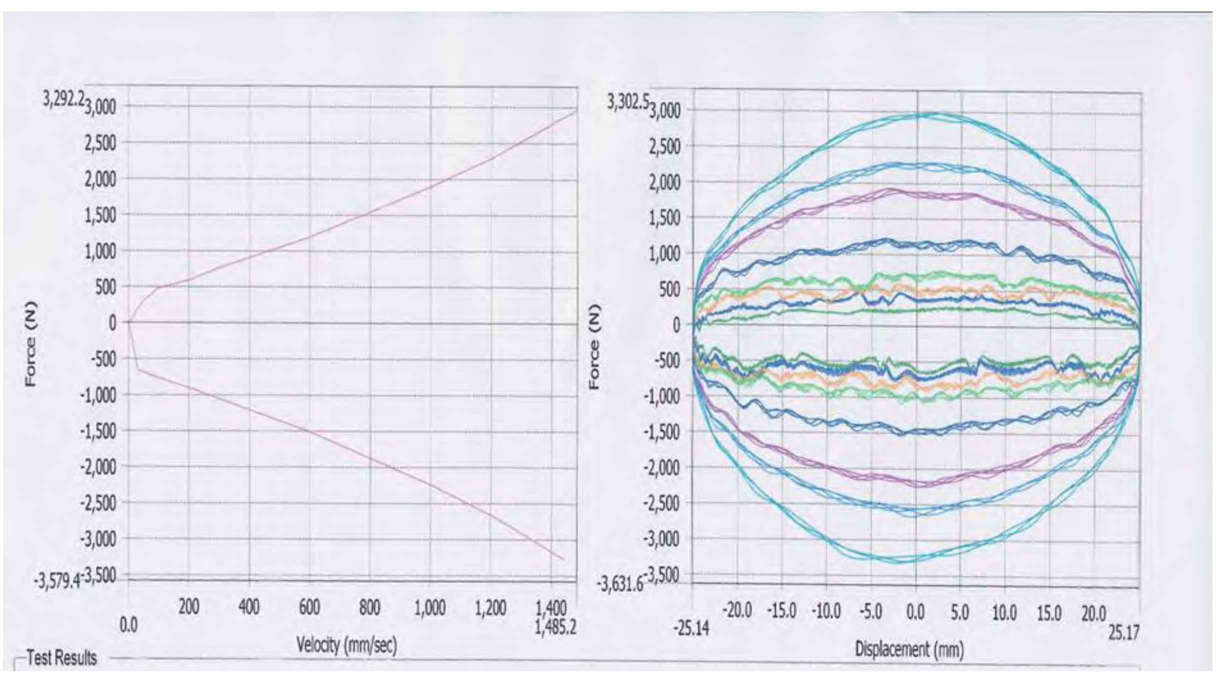



**Figure 4.18-171: Rear Suspension Damper Characteristics Baseline Model**

## 5) Other Components

Surrogate information utilizing engineering judgment and historical data for the following components was used as required to complete the model and achieve correlation to K&C results:

- Bushings
- Steering System
- Jounce Bumpers
- Tires
- Other

## 6) Weight Estimations

The target mass, CG and inertias for the baseline ADAMS/Chassis model were the measured data from VIMF. Targets for the Optimized version were based on the percent-change as shown in **Table 4.18-48** using the optimized full vehicle FEA model.

**Table 4.18-48: Mass, Inertia and CG Targets for Baseline and Optimized Models**

| | Configuration: 4x4, Crew Cab, 5.3L<br>Condition: Curb | | Total (kg) | Total (N) | Dist. (%) | Unsprung (kg) | Sprung (kg) | CG Height (mm) | Pitch Inertia (kg-m^2) | Yaw Inertia (kg-m^2) | Roll Inertia (kg-m^2) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Calculated Targets for ADAMS Model | Baseline Target (VIMF Measured) | Front Axle | 1443.80 | 14164 | 58.1% | 165.0 | 1278.8 | 718.6 | 6381 | 6781 | 1090 |
| | | Rear Axle | 1041.60 | 10218 | 41.9% | 215.0 | 826.6 | | | | |
| | | | 2485.40 | 24382 | | 380.0 | 2105.4 | | | | |
| | Hybrid-Aluminum Target | Front Axle | 1099.64 | 10788 | 58.0% | 101.4 | 998.2 | 714.6 | 4704 | 4997 | 795.0 |
| | | *% of Baseline* | *76.2%* | | | *61.4%* | | *99.4%* | *73.7%* | *73.7%* | *72.9%* |
| | | Rear Axle | 797.00 | 7819 | 42.0% | 146.8 | 650.2 | | | | |
| | | *% of Baseline* | *76.5%* | | | *68.3%* | | | | | |
| | | Total | 1896.65 | 18606 | | 248.2 | 1648.4 | | | | |
| | | *% of Baseline* | *76.3%* | | | *65.3%* | | | | | |

## 7) Occupant and Cargo Positions

To establish occupant and cargo positions for the ADAMS/Chassis model, physical measurements were taken as shown in **Figure 4.18-172**.

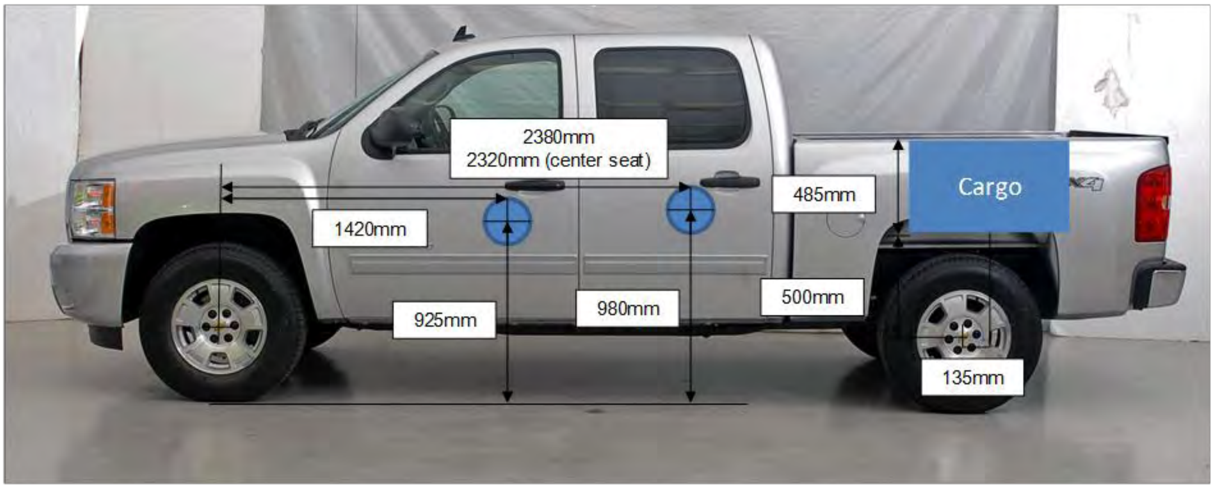



**Figure 4.18-172: Occupants Positions and Cargo Measurements**
*(Source: EDAG)*

The occupant positions and cargo positions used in the model are given in **Table 4.18-49**.

**Table 4.18-49: Occupant and Cargo Positions**

| Occupant Position (vehicle coordinates) | X | Y | Z |
|---|---|---|---|
| Driver | -3204 | -450 | 158 |
| Passenger | -3204 | 450 | 158 |
| Center Front | -3204 | 0 | 158 |
| Left Rear | -2244 | -450 | 193.3 |
| Right Rear | -2244 | 450 | 193.3 |
| Center Rear | -2304 | 0 | 193.3 |

| Cargo Position (vehicle coordinates) | X | Z |
|---|---|---|
| Rear WC | -971.9 | -436.6 |
| Delta | 135 | 742.5 |
| Cargo CG | -836.9 | 305.9 |

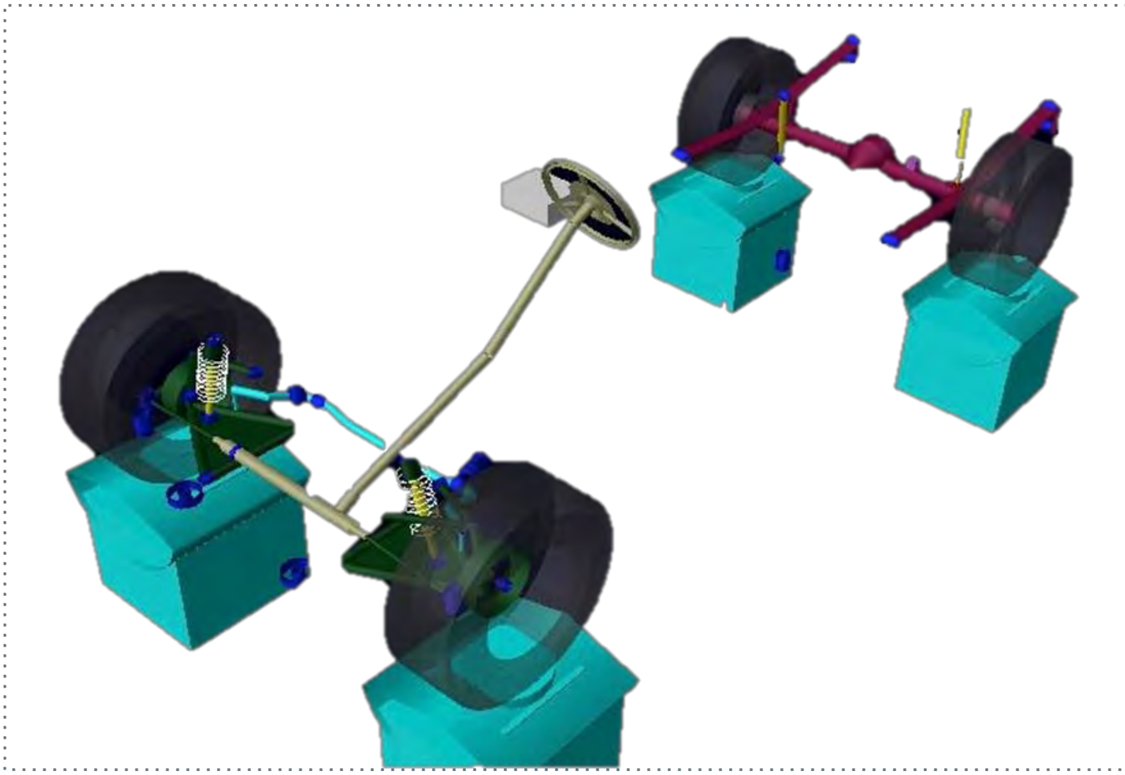


**Figure 4.18-173: Vehicle Dynamics Model**

4.18.5.6.2 Vehicle Dynamic Results Comparison

MSC ADAMS/Chassis code was used to simulate the vehicle static and dynamics characteristics of both baseline and optimized configurations. The results comparisons of optimized (light-weight) vehicle model for different loading conditions are provided as follows.

### 1) Static Vehicle Characteristics

The basic static vehicle and suspension characteristics are shown in **Table 4.18-50**. All results assume maintaining baseline ride height at GVW.

**Table 4.18-50: Static Characteristics of Baseline and Optimized Models**

| | | Baseline | | | | | Hybrid-Aluminum | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Condition | | Curb | 1-pass | 2-pass | 5-pass | GVW | Curb | 1-pass | 2-pass | 5-pass | GVW |
| Passengers | | 0 | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg | 0 | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg |
| Cargo | | 0 | 0 | 0 | 0 | 314 kg | 0 | 0 | 0 | 0 | 314 kg |
| **Axle Mass, CG, SSF** | | | | | | | | | | | |
| Front Axle | [kg] | 1443.8 | 1491.7 | 1539.6 | 1623.7 | 1607.9 | 1100.0 | 1147.9 | 1195.9 | 1280.3 | 1264.6 |
| Rear Axle | [kg] | 1039.3 | 1066.7 | 1094.1 | 1235.9 | 1566.2 | 796.6 | 824.0 | 851.3 | 992.8 | 1323.0 |
| Total | [kg] | 2483.1 | 2558.4 | 2633.7 | 2859.6 | 3174.1 | 1896.6 | 1971.9 | 2047.2 | 2273.1 | 2587.6 |
| CG Height | [mm] | 718.6 | 725.2 | 731.3 | 749.8 | 765.6 | 714.6 | 724.0 | 732.4 | 757.0 | 776.1 |
| SSF | [T/2H] | 1.197 | 1.186 | 1.176 | 1.147 | 1.123 | 1.203 | 1.188 | 1.174 | 1.136 | 1.108 |
| **Ride Height** | | | | | | | | | | | |
| Front Ride Height (from "design") | [mm] | 17.1 | 12.1 | 7.1 | -1.8 | 0.0 | 22.3 | 15.9 | 9.4 | -2.0 | 0.3 |
| Rear Ride Height (from "design") | [mm] | 57.9 | 54.4 | 50.8 | 32.3 | 0.0 | 71.4 | 66.9 | 62.5 | 39.3 | -1.0 |
| **Spring Rate** | | | | | | | | | | | |
| Front | [N/mm] | 135 | 135 | 135 | 135 | 135 | 100 | 100 | 100 | 100 | 100 |
| Rear | [N/mm] | 37 | 37 | 37 | 37 | 37 | 29 | 29 | 29 | 29 | 29 |
| **Wheel Rate** | | | | | | | | | | | |
| Front | [N/mm] | 45.7 | 45.4 | 45.2 | 45.0 | 45.1 | 35.8 | 35.6 | 35.4 | 35.1 | 35.2 |
| Rear | [N/mm] | 33.6 | 33.6 | 33.5 | 33.1 | 46.1 | 27.5 | 27.4 | 27.4 | 27.0 | 39.7 |
| **Ride Rate** | | | | | | | | | | | |
| Front | [N/mm] | 39.1 | 39.0 | 38.8 | 38.6 | 38.7 | 31.7 | 31.5 | 31.3 | 31.1 | 31.2 |
| Rear | [N/mm] | 30.3 | 30.3 | 30.3 | 29.9 | 40.2 | 25.2 | 25.2 | 25.2 | 24.8 | 35.2 |
| **Ride Frequency (based on ride rate)** | | | | | | | | | | | |
| Front | [Hz] | 1.24 | 1.22 | 1.20 | 1.16 | 1.17 | 1.27 | 1.23 | 1.20 | 1.16 | 1.17 |
| Rear | [Hz] | 1.36 | 1.34 | 1.32 | 1.22 | 1.23 | 1.41 | 1.38 | 1.35 | 1.22 | 1.23 |
| **Roll Rate (at the wheel)** | | | | | | | | | | | |
| Front | [Nm/deg] | 2359 | 2353 | 2348 | 2342 | 2347 | 1805 | 1798 | 1793 | 1786 | 1790 |
| Rear | [Nm/deg] | 583 | 578 | 573 | 546 | 740 | 490 | 484 | 478 | 447 | 632 |

- Rise-to-Curb is greater with the optimized model (lighter vehicle)

- CG height at the loaded conditions is higher – cargo is larger percentage of overall sprung mass

- Optimized model shows significant reduction in spring rate and roll rate (to match baseline performance) offer additional weight savings to the springs and anti-roll bar themselves. Actual spring weight reduction requires a full design analysis to predict; front ARB diameter is reduced by 3.5mm (approximately 10%) equating to a 15-20% weight savings (approx. 2.6 kg)

## 2) Dynamic Characteristics

The following events were chosen to compare the Vehicle Dynamics performance of the baseline and optimized models. These are standard events used in the development and evaluation of high-CG vehicles and were chosen because they demonstrate key aspects of vehicle behavior:

## I. Constant Radius:

Vehicle is driven around a circle of constant radius (200ft or 61m) through the linear handling range up to the limit of adhesion. This maneuver defines the steady-state behavior of the vehicle through the linear range and includes the following metrics:

- Understeer Gradient
- Front and Rear Cornering Compliance
- Roll Gradient

A summary of On-Road dynamic characteristics for Constant Radius event is shown in **Table 4.18-51**.

**Table 4.18-51: Constant Radius Characteristics of Baseline and Optimized Models**

| | | Baseline | | | | Hybrid-Aluminum | | | |
|---|---|---|---|---|---|---|---|---|---|
| Condition | | 1-pass | 2-pass | 5-pass | GVW | 1-pass | 2-pass | 5-pass | GVW |
| Passengers | | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg |
| Cargo | | 0 | 0 | 0 | 314 kg | 0 | 0 | 0 | 314 kg |
| Constant Radius | | | | | | | | | |
| Roll Gradient (total) | [deg/G] | 6.00 | 6.31 | 6.98 | 7.37 | 5.52 | 5.90 | 6.65 | 7.05 |
| Roll Gradient (body-on-chassis) | [deg/G] | 4.64 | 4.90 | 5.39 | 5.57 | 4.47 | 4.80 | 5.38 | 5.57 |
| Load Transfer Dist. | [% Front] | 61.38 | 61.61 | 60.67 | 55.00 | 60.58 | 60.91 | 60.62 | 53.18 |
| Front Weight and Tires | [deg/G] | 5.69 | 6.00 | 6.43 | 6.52 | 4.49 | 4.76 | 5.17 | 5.24 |
| Rear Weight and Tires | [deg/G] | -3.77 | -3.85 | -4.20 | -5.14 | -3.34 | -3.40 | -3.67 | -4.49 |
| Front Roll Steer | [deg/G] | 0.30 | 0.32 | 0.35 | 0.35 | 0.35 | 0.37 | 0.40 | 0.43 |
| Rear Roll Steer | [deg/G] | 0.01 | 0.03 | 0.17 | 0.38 | -0.08 | -0.05 | 0.10 | 0.39 |
| Front Suspension Compliance | [deg/G] | 1.53 | 1.61 | 1.74 | 1.73 | 1.07 | 1.14 | 1.27 | 1.28 |
| Rear Suspension Compliance | [deg/G] | -0.38 | -0.41 | -0.49 | -0.60 | -0.31 | -0.33 | -0.40 | -0.50 |
| Upstream Steering System | [deg/G] | -0.03 | -0.04 | -0.05 | -0.03 | 0.06 | 0.03 | 0.00 | 0.03 |
| Front Subtotal | [deg/G] | 7.50 | 7.90 | 8.46 | 8.57 | 5.96 | 6.30 | 6.85 | 6.99 |
| Rear Subtotal | [deg/G] | -4.15 | -4.22 | -4.52 | -5.35 | -3.73 | -3.78 | -3.97 | -4.60 |
| Total Understeer | [deg/G] | 3.35 | 3.68 | 3.94 | 3.22 | 2.23 | 2.52 | 2.88 | 2.39 |

From **Table 4.18-51**, it is observed that the optimized vehicle shows a reduced Linear-Range Understeer. Less weight results in reduced cornering compliance effects from the tires and reduced suspension compliance effects.

The Constant Radius event results are also plotted for Steering Wheel Angle (SWA) and Front/Rear cornering compliance (in terms of Slip Angle) with respect to lateral accelerations. **Figure 4.18-174** shows the steering wheel angle comparison, and **Figure 4.18-175** shows the slip angle comparison. The results are interpreted as acceptable.

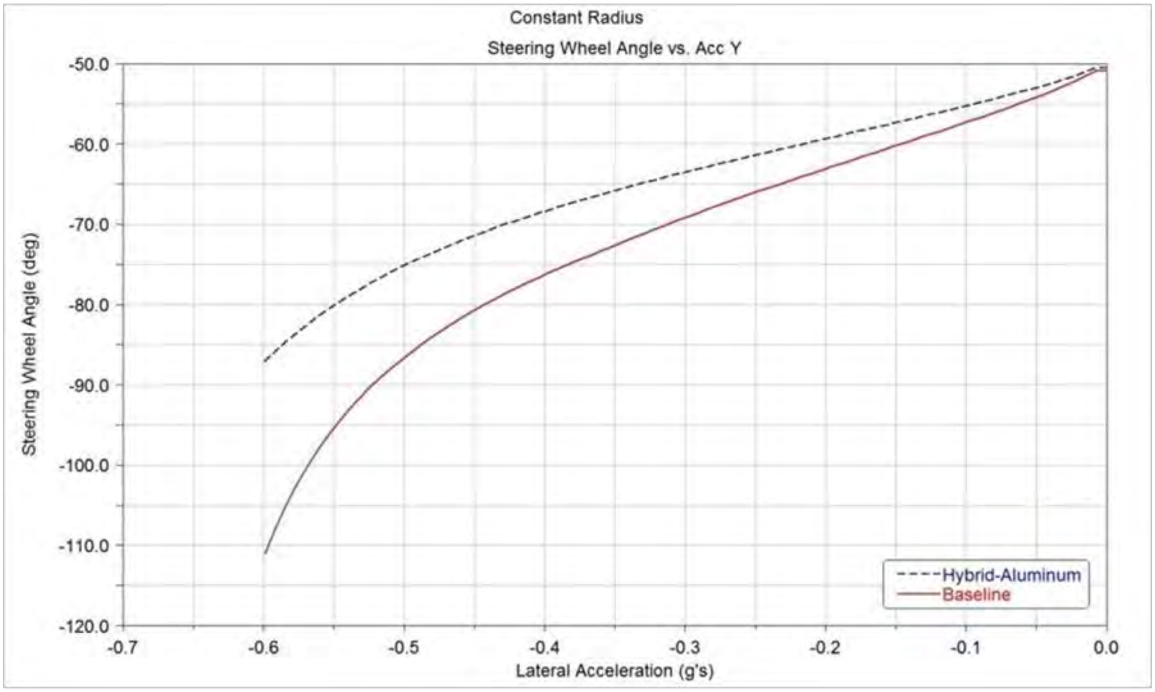



**Figure 4.18-174: Steering Wheel Angle of Baseline and Optimized Models**

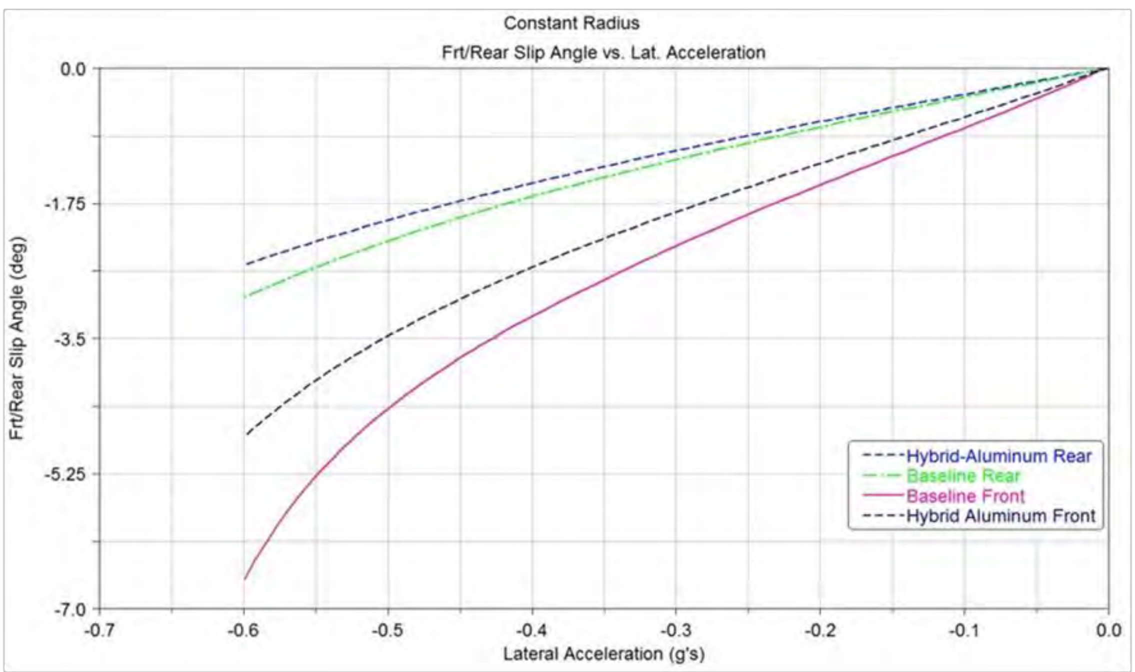



**Figure 4.18-175: Front/Rear Cornering Compliance**

**Table 4.18-52** also shows the total understeer due to front and rear cornering.

**Table 4.18-52: Understeer of Baseline and Optimized Models**

| Condition: 2-Pass | Baseline | Optimized |
|---|---|---|
| Front Cornering Compliance (deg/G) | 7.90 | 6.30 |
| Rear Cornering Compliance (deg/G) | -4.22 | -3.78 |
| Total Understeer @ Road Wheel (deg/G) | 3.68 | 2.52 |

- The typical Total Understeer @ Road Wheel range for this type of vehicle would be 2-5 deg/G
- Both the Baseline and Hybrid-Aluminum variants show acceptable performance.

## II. J-Turn:

Vehicle driven in a straight line and a specified hand wheel angle (90, 180, 270, 360 degrees used for this study) is applied at a rate of 1,000 deg/sec and held. This maneuver is used to help define the roll stability of high-CG vehicles and the acceptance criteria are no simultaneous two-inch or greater lift of the vehicle's inside tires (two-wheel lift).

A summary of on-road dynamic characteristics for J-Turn event is shown in **Table 4.18-53**.

**Table 4.18-53: J-Turn Tire Loads of Baseline and Optimized Models**

| | | Baseline | | | | Hybrid-Aluminum | | | |
|---|---|---|---|---|---|---|---|---|---|
| Condition | | 1-pass | 2-pass | 5-pass | GVW | 1-pass | 2-pass | 5-pass | GVW |
| Passengers | | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg |
| Cargo | | 0 | 0 | 0 | 314 kg | 0 | 0 | 0 | 314 kg |
| J-Turn | | | | | | | | | |
| Min. Combined Inside Tire Load (90 deg SWA) | [N] | 4613 | 4812 | 5179 | 5383 | 2678 | 2763 | 3237 | 3455 |
| Min. Combined Inside Tire Load (180 deg SWA) | [N] | 3424 | 3482 | 3919 | 4695 | 1457 | 1464 | 1597 | 2483 |
| Min. Combined Inside Tire Load (270 deg SWA) | [N] | 3387 | 3465 | 3730 | 4448 | 1416 | 1425 | 1561 | 2401 |
| Min. Combined Inside Tire Load (360 deg SWA) | [N] | 3484 | 3566 | 3865 | 4525 | 1465 | 1449 | 1577 | 2414 |

From **Table 4.18-53** that the optimized vehicle shows a less combined inside tire load. This is due to the large reduction in weight and similar CG height.

The optimized model does not saturate the tires as quickly during the abrupt J-Turn maneuver which contributes to additional load transfer.

The combined inside tire load trend of optimized model is shown in **Figure 4.18-176** with respect to the baseline.

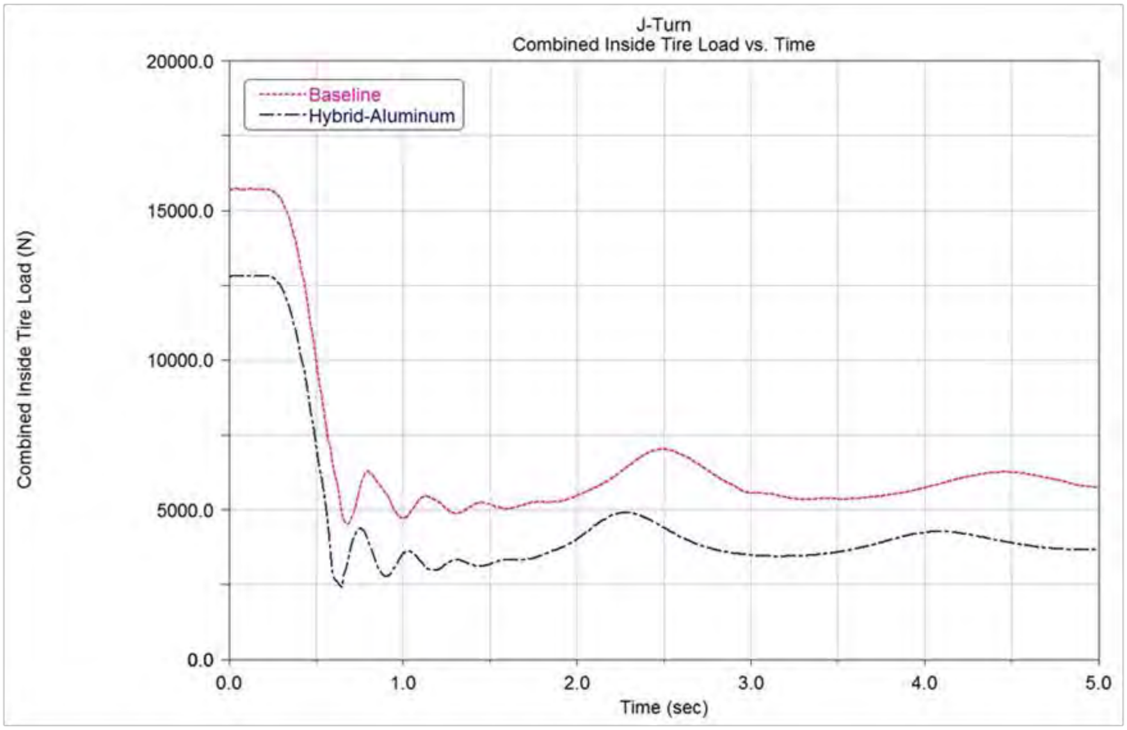



**Figure 4.18-176: Combined Tire Load**

It is observed that the baseline and optimized vehicle show acceptable J-Turn performance using a surrogate tire model with no simultaneous two-inch or greater lift of the vehicle's inside tires (two-wheel lift).

## III. Frequency Response:

Vehicle driven at a constant speed while a sinusoidal steering input of increasing frequency is applied to achieve a specific G-level (0.32G @ 120kph was used for this study). This maneuver is used to help define the steering response of the vehicle and includes the following metrics.

- Gain (amount of response)
- Phase Lag (time delay of response)

A summary of On-Road dynamic characteristics for J-Turn event is shown in **Table 4.18-54**.

**Table 4.18-54: Frequency Response Characteristics of Baseline and Optimized Models**

| | | Baseline | | | | Hybrid-Aluminum | | | |
|---|---|---|---|---|---|---|---|---|---|
| Condition | | 1-pass | 2-pass | 5-pass | GVW | 1-pass | 2-pass | 5-pass | GVW |
| Passengers | | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg |
| Cargo | | 0 | 0 | 0 | 314 kg | 0 | 0 | 0 | 314 kg |
| Frequency Response @ 120kph | | | | | | | | | |
| Yaw Gain Steady State | [deg/s/100degSWA] | | 17.3 | | | | 21.3 | | |
| Yaw Rate 45deg Phase Lag | [ms] | | 112.8 | | | | 100.8 | | |

From **Table 4.18-54**, it is observed that optimized vehicle shows higher Steady State Yaw Gain, indicating more response than the baseline vehicle. Optimized vehicle also shows lower Phase Lag, indicating quicker response to inputs than the baseline vehicle.

- Typical Steady State Yaw Gain range for this type of vehicle would be 15-25 deg/s/100degSWA – Baseline and optimized vehicles exhibit acceptable performance.
- Typical Phase Lag range for this type of vehicle would be 90-115 milliseconds – Baseline and optimized vehicles exhibit acceptable performance.

**Other Results – Dynamic Characteristics**

**FMVSS126 Summary:** FMVSS126 is the NHTSA-mandated test to evaluate the effectiveness of a vehicle's Electronic Stability Control (ESC) system at preventing "single-vehicle loss-of-control, run-off-the-road crashes, of which significant portions are rollover crashes." (Source: NHTSA FMVSS126) The physical vehicle test is performed with the ESC system fully functional which is beyond the scope of the Vehicle Dynamics simulations performed in this study.

**NHTSA Fishhook:** Fishhook is a test used by NHTSA to evaluate a "vehicle's susceptibility to an on-road un-tripped rollover in which the vehicle is subjected to tire/road interface friction forces in extreme maneuvers, but not to the much greater forces caused by off-road tripping mechanisms." (Source: NHTSA) The physical vehicle test is performed with the ESC system fully functional which is beyond the scope of the Vehicle Dynamics simulations performed in this study.

**Static Stability Factor (SSF):** NHTSA has declared a key contributor to vehicle rollover risk is a vehicle's SSF, defined as vehicle track width/ (2 x CG height). For the different variants in this study, the SSF of each is summarized in **Table 4.18-55**.

**Table 4.18-55: Static Stability Factor Characteristics of Baseline and Optimized Models**

| | | Baseline | | | | | Hybrid-Aluminum | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Condition | | Curb | 1-pass | 2-pass | 5-pass | GVW | Curb | 1-pass | 2-pass | 5-pass | GVW |
| Passengers | | 0 | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg | 0 | 1 x 75.25 kg | 2 x 75.25 kg | 5 x 75.25 kg | 5 x 75.25 kg |
| Cargo | | 0 | 0 | 0 | 0 | 314 kg | 0 | 0 | 0 | 0 | 314 kg |
| Axle Mass, CG, SSF | | | | | | | | | | | |
| CG Height | [mm] | 718.6 | 725.2 | 731.3 | 749.8 | 765.6 | 714.6 | 724.0 | 732.4 | 757.0 | 776.1 |
| Track Width (average) | [mm] | 1719.8 | 1719.8 | 1719.8 | 1719.8 | 1719.8 | 1719.8 | 1719.8 | 1719.8 | 1719.8 | 1719.8 |
| SSF | [T/2H] | 1.197 | 1.186 | 1.176 | 1.147 | 1.123 | 1.203 | 1.188 | 1.174 | 1.136 | 1.108 |

- Based on the minimal differences in SSF shown in Table 4.18-55, it is judged that the ESC systems of the optimized vehicle is feasible to be successfully developed to pass FMVSS126 requirements and the NHTSA Fishhook test.

Overall summary and additional considerations of the effects on Vehicle Dynamics and the Chassis system of the optimized vehicle are as follows:

The ADAMS/Chassis model predicts acceptable performance for Constant Radius, J-Turn and Frequency Response tests.

Additionally, overall weight reduction has beneficial effects for Vehicle Dynamics in the following areas:

- Sprung and unsprung masses are easier to control resulting in improved roll damping and ride characteristics
- Lower weight and roll/pitch/yaw inertias allow more opportunity for trade-off between steering performance and roll/yaw stability
- Reduced loads into suspension and body components allowing a better trade-off between Ride/Handling/Steering and Durability requirements

When maintaining the same load-carrying capability and cargo location on a lighter vehicle, it generally has to operate through a wider range of suspension travel. This can have effects on:

- Rise-to-Curb and reserve travel at various operating conditions
- CG height change with load

Reduced spring rates and front anti-roll bar diameter are required to maintain the same ride frequency and roll gradient of the lightweight variant. This offers additional 'secondary' weight savings due to lighter components. Changes are as follows:

- Front spring rate reduced by 26% - actual weight reduction estimate requires design analysis

- Rear spring rate reduced by 22% - actual weight reduction estimate requires design analysis
- Front anti-roll bar (ARB) diameter reduced by 3.5mm (approximately 10%) – 15-20% weight savings (approximately 2.6 kg)

#### 4.18.5.7 Frame Durability Performance Results

To assess the durability of the frame structure a process was developed to build a correlated Multi-Body Dynamics Model (MBD) in Motion View and use this model to generate fatigue loads for analysis of both the baseline and new lightweight frame designs. In order to do this, suspension geometry was calculated from CMM data collected at the MGA proving grounds, a kinematic suspension model was created, bushing rates / curves were developed to correlate the model with measured K&C data, wheel spindle accelerations were collected at the MGA proving grounds, analytical loadcases were developed and validate by comparison with the MGA proving ground data, loadcases were defined in terms of corner weights so they could be adjusted appropriately with the vehicle weight reductions and finally the loadcases had to be checked to ensure they were properly scaled such that the baseline frame passed when performing the fatigue analysis.

In developing this process some basic assumptions were made. These included the CMM data accuracy was ±3 mm (hardpoints could move within this range to better match kinematics data) and the frame and part stiffness were not included in the model.

For this study, the final assumption was made that the fatigue performance of the frame would correspond to the overall full vehicle durability performance. The EDAG CAE frame model was then evaluated for fatigue with these results considered representative of the overall vehicle durability performance. The bases of this assumption are that with all of the input loads being transmitted through the frame and with the isolation of the cabin failures seen in the frame would drive the overall vehicle performance. It is recognized that this is an over simplification of vehicle structural durability but within the scope of the program this approach was felt to be reasonable for the various comparative studies. Therefore, based on this simply assumption, only the frame was evaluated for fatigue loads.

The fatigue analysis of frame involved the following steps:

1) Develop a Multi-Body Dynamics Model
2) Develop analytical Loadcases
3) Perform Stress and Fatigue analysis

## 1) Multi-Body Dynamics Model Development (MBD)

For fatigue analysis, loads were generated using multi-body dynamics simulation software called Altair MotionView. The suspension geometry was developed from the CMM data collected at the MGA proving ground. Bushing rates/curves were developed and correlated with the measured K & C data. The developed MBD model is shown in **Figure 4.18-177**. An example of the correlation between the MotionView and K & C data is shown in **Figure 4.18-178**.

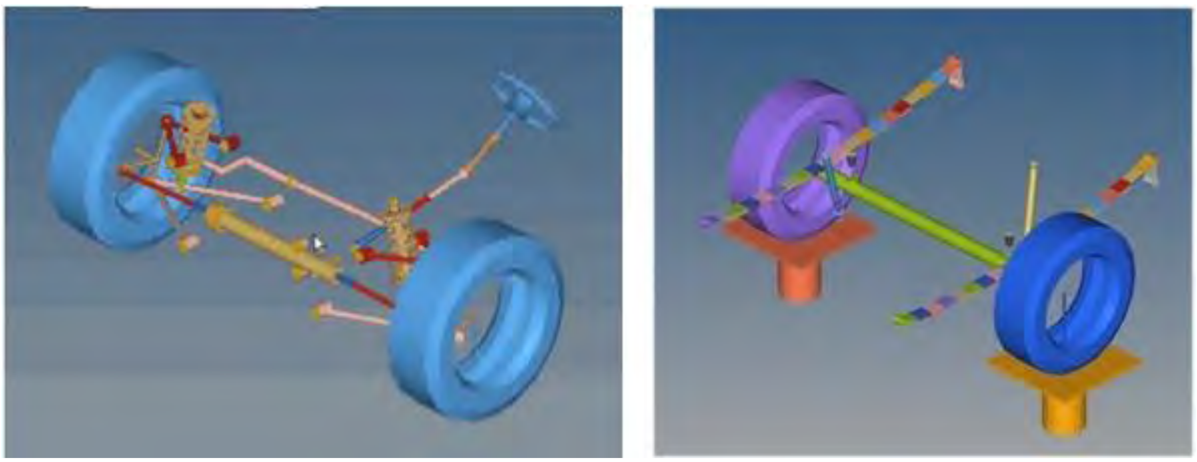
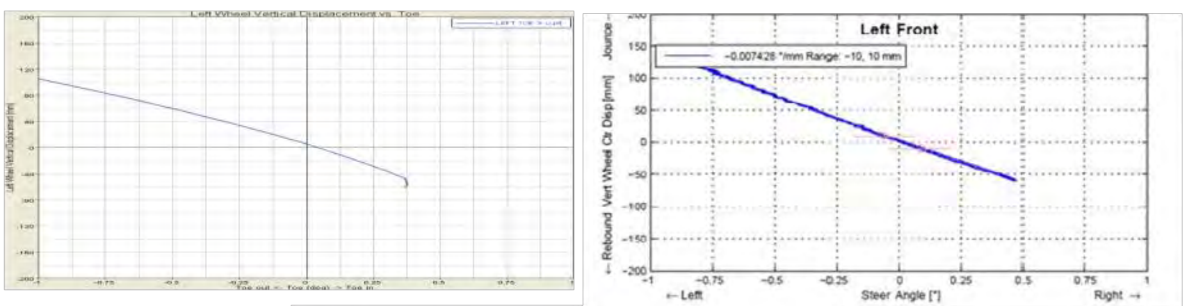


**Figure 4.18-177: Front and Rear Suspension (MotionView Model)**

**Wheel Travel vs. Steer Angle**

MotionView K&C




| | Unit | Motion-View | K&C (L/R Avg.) |
|---|---|---|---|
| Bump Steer | deg/m | -8.12 | -9.06 |

**Figure 4.18-178: MotionView versus K & C data comparison**

## 2) Analytical Loadcases

Frame loads were generated from an initial set of static loadcases based on experiences from previous vehicle development programs. In the static loadcases, static loads were inputted at the wheel center, tire patch and shock attachments. The loads applied to the shock attachments were not dynamic shock loads. They were surrogate forces to account for the fact that these were static loadcases and dynamic shock loads were therefore zero. Additionally, for this study the body was considered fixed to the ground. **Figure 4.18-179** and **Figure 4.18-180** show the front and rear suspension loading arrangement. The model was solved for static equilibrium and force/moment reactions were computed at all attachment locations. Loads for the lightweight models were scaled based on the mass.

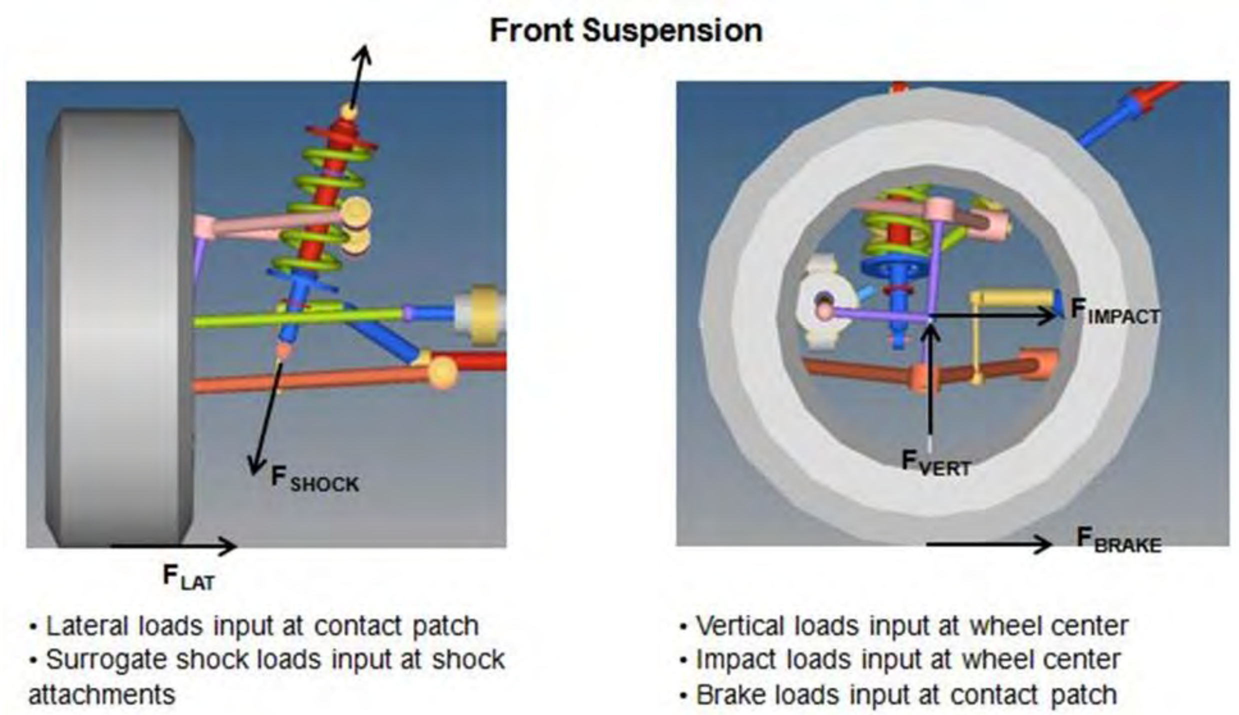



**Figure 4.18-179: Front Suspension**

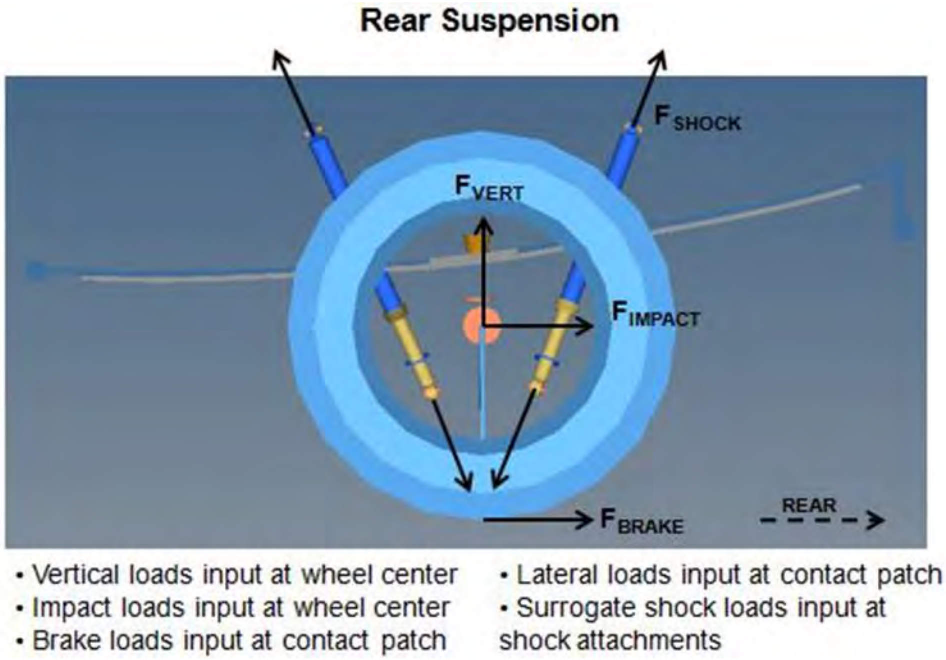



**Figure 4.18-180: Rear Suspension**

Inputs in static loadcases were defined as multipliers of vehicle corner weight. These multipliers were then scaled in an iterative process such that the loads generated allowed the baseline frame to pass fatigue. The same multipliers were used for both the baseline and lightweight optimized frame. As a result, these loads were scaled proportionally when applied to lightweight optimized frame.

Analytical loadcases were validated by comparison with equivalent static loads determined from accelerometer measurements taken at the MGA proving grounds. The instrumentation and proving ground events are shown in **Image 4.18-2** and **Figure 4.18-181**, respectively.

Instrumentation: Left Front Spindle Accelerometer

LF Spindle Accelerometer XYZ

**Image 4.18-2: Instrumentation – Left Front Spindle Accelerometer**
*(Source: EDAG)*

MGA Proving Ground Events

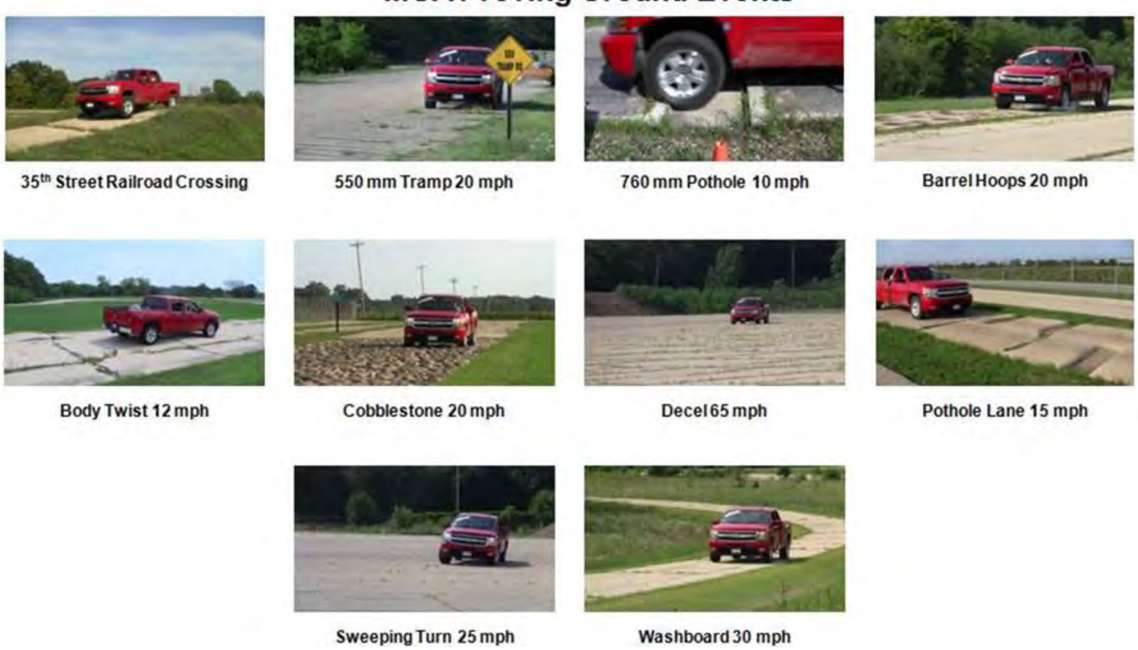



**Figure 4.18-181: MGA Proving Ground Events**

### 3) Stress and Fatigue Analysis

The baseline and lightweight optimized frame FEA Models were set up in Altair Hypermesh. **Figure 4.18-182** shows loading and constraints in the front loadcases and **Figure 4.18-183** shows loading and constraints in the rear loadcases.

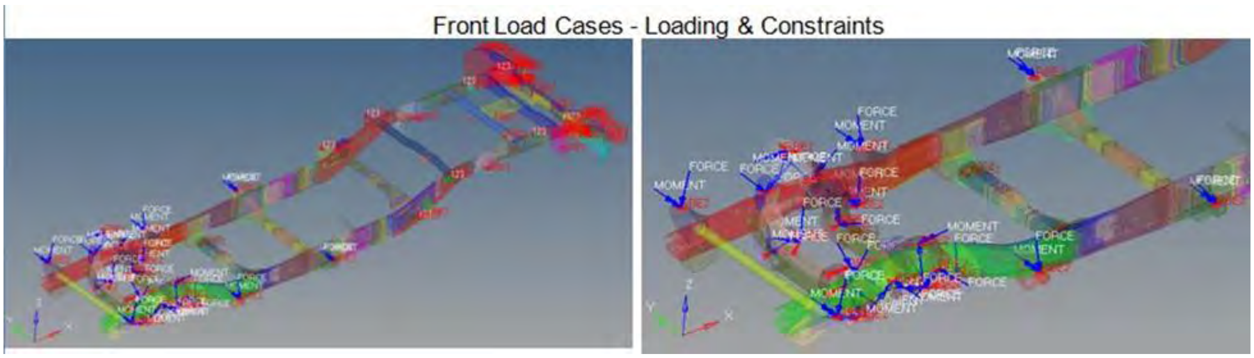



**Figure 4.18-182: FEA Model: Front Loadcases**

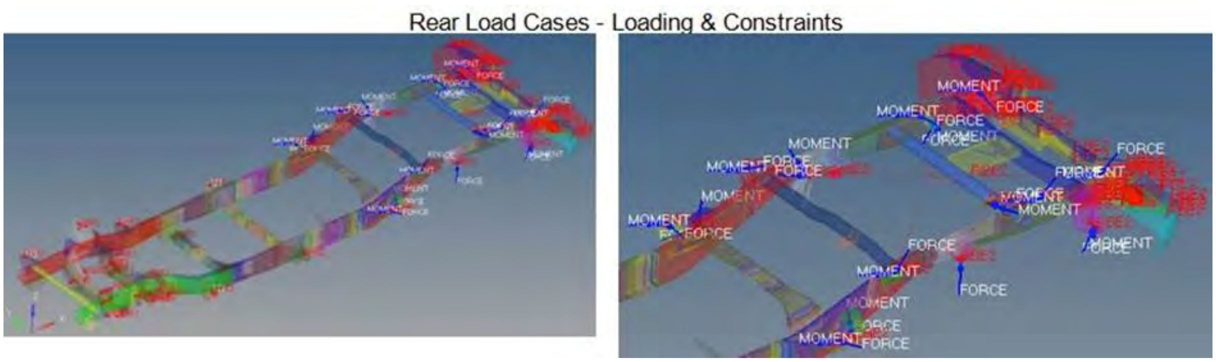



**Figure 4.18-183: FEA Model: Rear Loadcases**

After model set up, Stress analysis was done using Altair's Optistruct solver with the front and rear loadcases shown above. Then Code Design Life solver was used to calculate fatigue life cycles in the front and rear loading events. **Figure 4.18-184** shows stress and fatigue analysis results of front curb loading event in the baseline frame and **Figure 4.18-185** shows stress and fatigue analysis results of front curb loading event in the lightweight optimized frame.

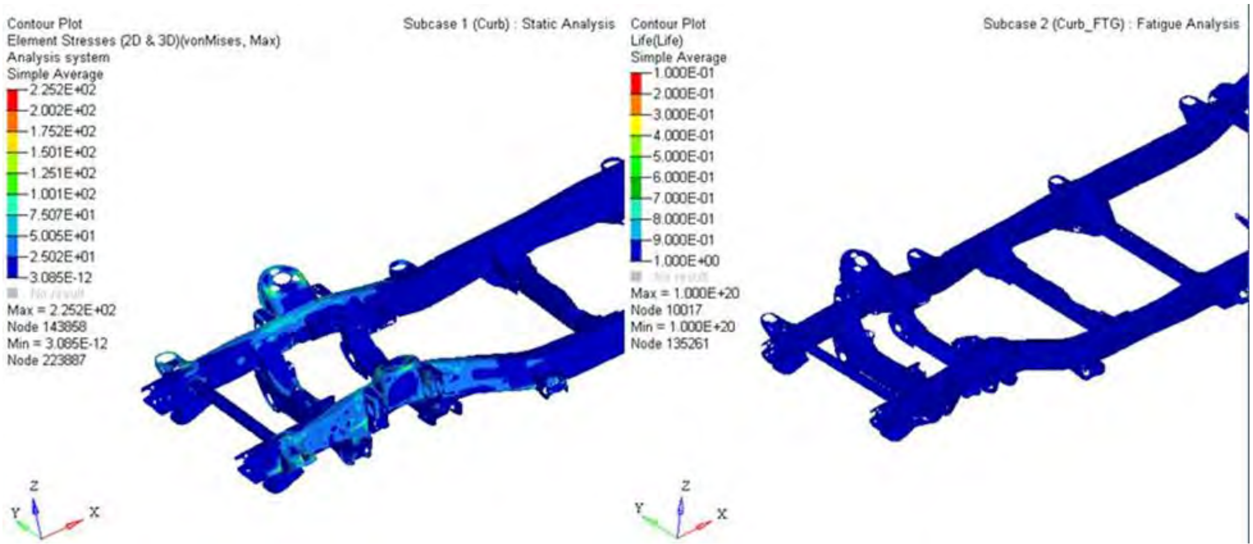



**Figure 4.18-184: Baseline Frame: Stress and Fatigue Results**

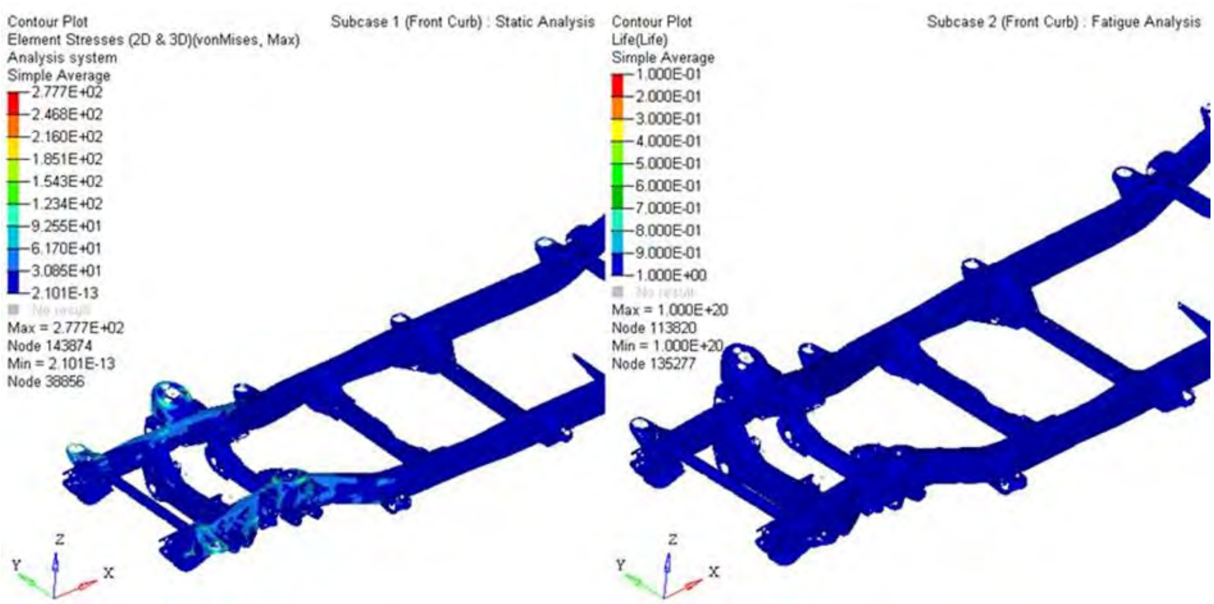



**Figure 4.18-185: Lightweight Optimized Frame: Stress and Fatigue Results**

## Result Summary

The results of the baseline frame and the lightweight optimized frame were compared and in the front loadcase events, there was a small reduction in fatigue life in the optimized frame as compared to the baseline frame which could be resolved with minor trim and weld changes (**Figure 4.18-186**).

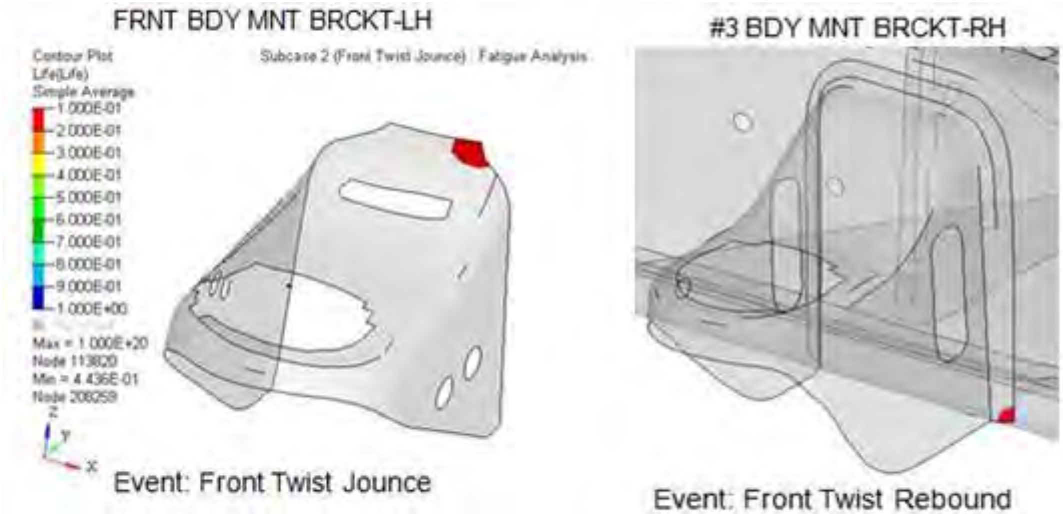



**Figure 4.18-186: Lightweight Optimized Frame: Front Loads Results**

In above example, the fatigue life of both mounts can be improved by minor trim and weld changes.

In the rear loadcase events, three components (#1 LHS cargo box mount bracket, #1 RHS cargo box mount bracket and the left hand front spring mount bracket) showed performance below baseline levels as shown in the example in **Figure 4.18-187**.

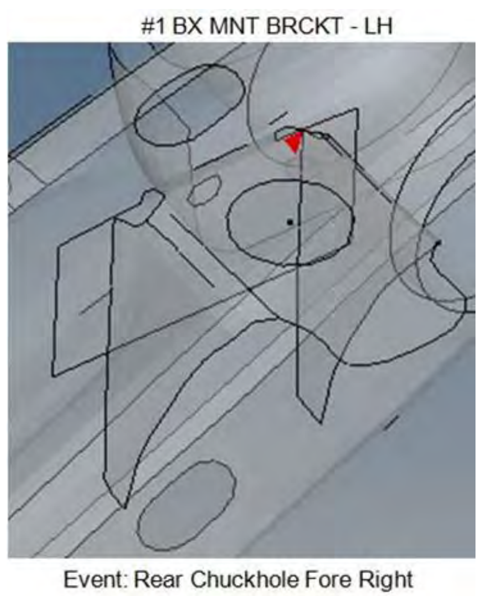



**Figure 4.18-187: Lightweight Optimized Frame: Rear Loads Results**

It should be noted that if all three of these components required up-gauging the overall potential increase in the mass of the frame would only be approximately 1.5 kg. However, before increasing the mass for these components it is recommended that the lightweight design be tested with the proposed gauges prior to making any changes. Therefore, this design and associated mass savings for the lightweight optimized model is judged to be acceptable when including the minor changes noted above and pending actual physical testing.

#### 4.18.5.8 Cost Impact

##### 4.18.5.8.1 Final Optimized Vehicle

The final optimized vehicle included the aluminum parts. Therefore, in addition to the parts manufacturing changes, assembly changes were also observed in number of assemblies. The assembly cost of replacing steel grades with aluminum were calculated based on the number of parts and connections in the assembly, type of connections, assembly equipment and tooling. The baseline vehicle assemblies were made up of resistance spot welding (RSW) whereas the optimized vehicle assemblies of aluminum parts were made up of self-piercing rivets (SPR), adhesives and bolted fasteners.

The assembly process of the steel parts in the baseline and the optimized vehicle were assumed to be same and there was no difference in the assembly cost. Similarly, the assembly process of doors and hood were assumed to be same with hemming and fastening irrespective of the steel version in baseline and aluminum version in optimized vehicle, therefore there was no difference noted in the assembly cost for the doors and hood. In the case of the Frame assembly, the steel cross member parts in baseline model and the corresponding aluminum cross members in the optimized model are bolted assemblies and therefore the assembly process in both models are assumed to be same resulting no difference in the assembly cost.

The only assemblies listed in **Table 4.18-56** were included in the assembly cost estimation.

**Table 4.18-56: Assemblies with Aluminum Parts for Cost Estimation**

| Assembly | Connection Type (Baseline) | Connection Type (Optimized) |
|---|---|---|
| **Body Structure Subsystem** | | |
| Box Assembly Pick-Up | RSW | SPR |
| Cabin | RSW | SPR |
| Panel Fender Outer LH | RSW | SPR |
| Panel Fender Outer RH | RSW | SPR |
| Radiator Structure | RSW | SPR & Fastening |
| IP XMbr Beam Assembly | RSW | SPR & Fastening |
| Extra Cabin - Radiator Support | RSW | SPR & Fastening |
| **Body Closures Subsystem** | | |
| Cargo Box Gate | RSW | SPR |
| **Bumpers Subsystem** | | |
| Bumper Front | RSW | SPR |
| Bumper Rear | RSW | SPR |

In case of the assembly cost, the material price of RSW is assumed to be \$0.45/electrode and material price of SPR is assumed to be \$0.04/rivet [52] The material prices were calculated by taking the electrode/rivet consumptions for each assembly. The other cost components such as Labor, Energy, Equipment, Tooling, Building, Maintenance, Overhead and Manufacturing $CO_2$ emissions costs were calculated by using the built-in formulas within the cost model spread sheet using the inputs listed in **Appendix Body and Frame Supporting Data, Section 7.2.9**. Additionally, in the optimized model the assembly of the aluminum parts included adhesive bonding at all SPR areas, resulting in an estimated adhesive length of 180 meters. The cost of adhesive was assumed to be \$20 per kg. The assumptions for estimating these costs are provided in **Table 7.2-3** through **Table 7.2-10** in **Appendix Section 7.2 Body and Frame Supporting Data**.

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52 Paul Briskham, Nicholas Blundell, Lin Han, Richard Hewitt and Ken Young., "Comparison of self-pierce riveting, resistance spot welding and spot friction joining for Aluminum automotive sheet.", SAE 2006

The manufacturing and assembly cost impacts of the final optimized vehicle are shown in **Table 4.18-57** and **Table 4.18-58**.

**Table 4.18-57: Manufacturing Cost Impact of Optimized Aluminum Vehicle with HSS/Aluminum Frame**

| Description | Estimated Mass Reduction[kg] "+" mass decrease | Estimated Cost Impact [$] "+" cost decrease | Average costs/kilogram[$/kg] |
|---|---|---|---|
| **Body Structure Subsystems** | | | |
| Box Assembly Pick-up | 34.4 | -216.44 | -6.29 |
| Frame Assembly | 23.7 | -54.42 | -2.30 |
| Cabin | 75.4 | -381.31 | -5.06 |
| Panel Fender Outer LH | 7.5 | -13.81 | -1.84 |
| Panel Fender Outer RH | 7.0 | -13.27 | -1.90 |
| Radiator Structure | 5.7 | -4.83 | -0.85 |
| IP XMbr Beam Assembly | 5.8 | -7.55 | -1.30 |
| Extra Cabin – Radiator Support | 5.9 | -38.30 | -6.49 |
| **Body Closures Subsystems** | | | |
| Hood Assembly w/o Hinges | 11.0 | -35.19 | -3.20 |
| Door Assembly Front LH | 10.2 | -58.99 | -5.78 |
| Door Assembly Front RH | 10.1 | -58.73 | -5.81 |
| Door Assembly Rear LH | 7.0 | -49.31 | -7.04 |
| Door Assembly Rear RH | 7.2 | -49.14 | -6.83 |
| Cargo Box –Tail Gate | 8.6 | -22.77 | -2.65 |
| **Bumpers Subsystems** | | | |
| Bumper Front | 9.9 | -19.72 | -1.99 |
| Bumper Rear | 6.5 | -42.64 | -6.56 |
| **Totals:** | **235.9** | **-1,066.42** | **-4.52** |

**Table 4.18-58: Assembly Cost Impact of Optimized Aluminum Vehicle with HSS/Aluminum Frame**

| Assembly Cost Going from Steel to Aluminum | | | |
|---|---|---|---|
| **Assembly** | **Baseline** | **Optimized** | **Cost Impact** |
| **Body Structure Subsystems** | | | |
| Box assy Pick-up | 18.71 | 36.59 | -17.88 |
| Cabin | 87.52 | 177.04 | -89.52 |
| Panel Fender Outer LH | 5.30 | 9.25 | -3.95 |
| Panel Fender Outer RH | 4.38 | 7.91 | -3.53 |
| Radiator Structure | 5.30 | 9.25 | -3.95 |
| IP XMem Beam assy | 8.23 | 15.70 | -7.47 |
| Extra Cabin – Radiator Support | 10.89 | 21.08 | -10.19 |
| **Body Closures Subsystems** | | | |
| Cargo Box – Gate | 3.79 | 6.17 | -2.38 |
| **Bumpers Subsystems** | | | |
| Bumper Front | 3.99 | 6.82 | -2.83 |
| Bumper Rear | 3.79 | 6.21 | -2.42 |
| **Adhesive** | 0 | 57.60 | -57.60 |
| **Totals:** | **151.90** | **353.62** | **-201.72** |
| "+" cost decrease, "-" cost increase | | | |

From the information in the tables, the overall weight savings on the light weight vehicle is 235.9 kg, with an incremental manufacturing cost of $1,066.42 ($4.52 per kg) and an incremental assembly cost of $201.72 ($0.85 per kg). The total increase in cost being $5.37 per kg.

### 4.18.6 Secondary Mass Reduction/Compounding

Table 4.18-59 summarizes the assignments of primary and secondary mass savings for the major Body and Frame Systems. Primary mass savings is defined as the mass a component or system can be reduced without impacting the functionality or overall performance of the baseline vehicle or component. This would typically be done through design and/or material changes. Secondary mass savings is defined as the mass reduction of a component or system as a direct result of an overall mass reduction in other areas. This allows the component or system to maintain the functionality or performance of the baseline vehicle while achieving a mass reduction. No additional analyses were done to determine the splits in primary/secondary percentages for the individual components within the systems.

**Table 4.18-59: Vehicle Secondary Mass Summary – Body and Frame Systems**

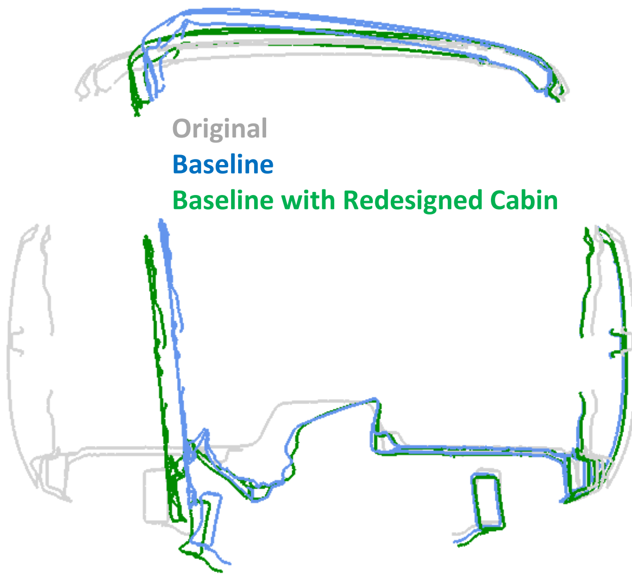
| Body and Frame Subsystems | Primary | Secondary |
|---|---|---|
| Body – Closures | Y | N |
| Cabin – Structure | Y | N |
| Cargo Box – Closure | Y | N |
| Cargo Box – Structure | Y | N |
| Frame | N | Y |
| Bumpers | N | Y |

The body closure subsystem includes the doors, fenders, and hood. The mass reductions accomplished on the body closures were classified as primary mass savings since the gross vehicle mass does not play a significant role in the performance targets of these systems. This is the same for the cargo box subsystem - closures and structure. In addition, the cargo box structure is expected to meet the same carrying criteria as in the baseline design. This expected performance requirement outweighs any potential mass reduction from the cargo box.

The assignments for the cabin structure and the frame subsystem were not as clear and as a result additional CAE analyses needed to be performed.

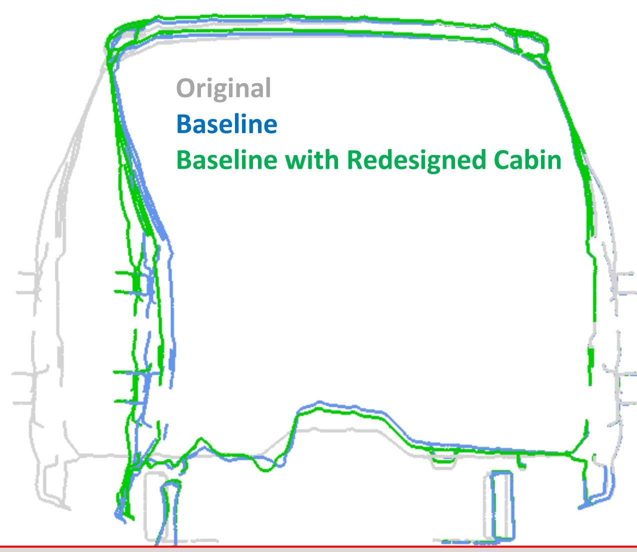
The mass reduced cabin structure design was installed into the baseline model and evaluated against the results of the FMVSS 214 5th Pole Impact crash test, the IIHS MDB Side Impact crash test and FMVSS 216a Roof Crush test. The results are shown in **Figure 4.18-188** through

**Figure** 4.18-190.



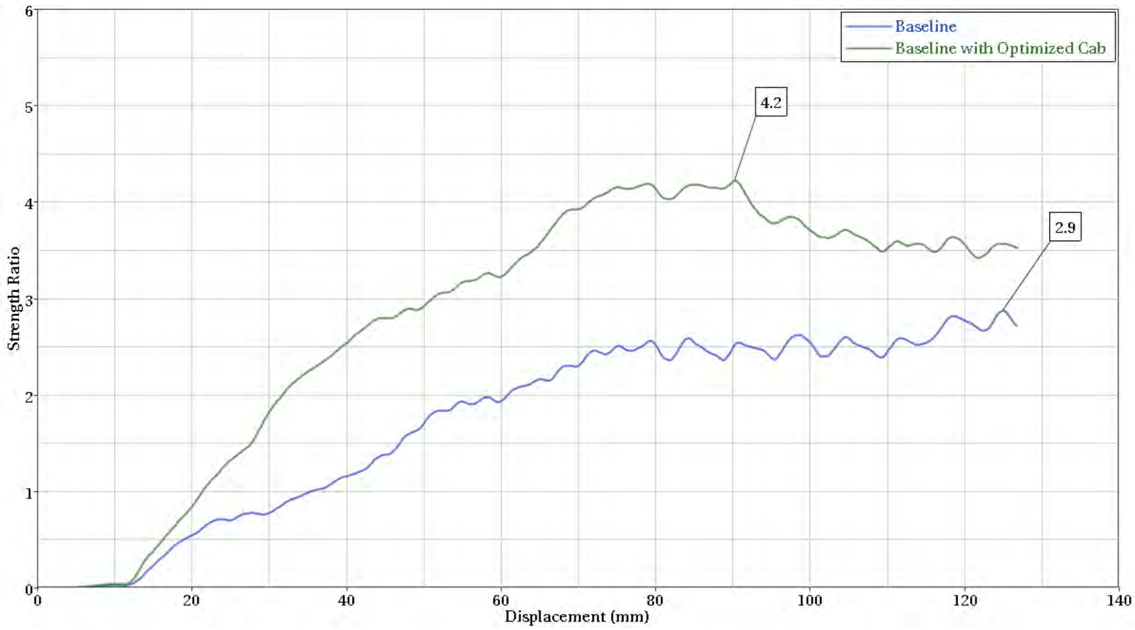

Intrusions are less with the redesigned cabin as seen in the above section

**Figure 4.18-188: FMVSS 214 5th Pole Impact – Results**




Intrusions are less with the redesigned cabin as seen in the above section

**Figure 4.18-189: IIHS MDB Side Impact – Results**




The baseline with redesigned cabin has a higher roof strength to weight ratio

**Figure 4.18-190: FMVSS 216a Roof Crush – Results**

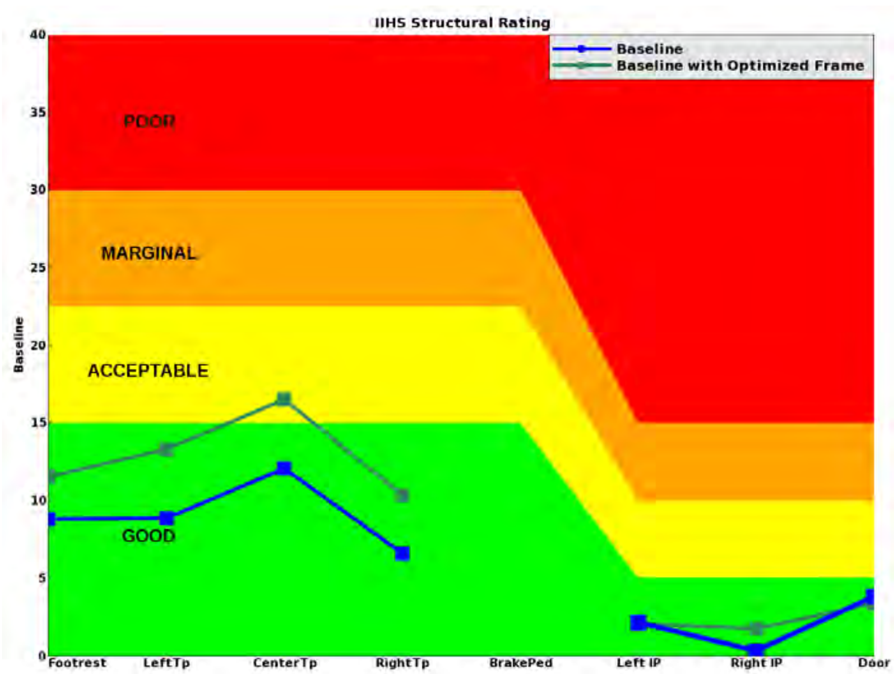
The vehicle results with only the redesigned cabin for FMVSS 214 5th Pole Impact crash test, the IIHS MDB Side Impact crash test and FMVSS 216a Roof Crush test show better performance when compared against the original baseline vehicle results. Therefore, it can be considered that the mass savings in the redesigned cabin is not a result of the overall mass reduction and can be classified as primary mass savings.

The mass reduced frame design was then installed into the original baseline model and evaluated against the baseline results for the FMVSS 208 Frontal Impact test and the IIHS Frontal Impact (ODB) test. The results of these comparisons are shown in **Table 4.18-60** and

**Figure** 4.18-191.

**Table 4.18-60: FMVSS 208 Frontal Impact – Results**

| | Event | Baseline Results | Baseline with Redesigned Frame Results |
|---|---|---|---|
| General Index | Max Acceleration (Average LH/RH) (g) | 38.0 | 38.7 |
| | Dynamic Crush (Average LH/RH) (mm) | 655.3 | 768.2 |
| | Time to Zero Velocity (Average LH/RH) (ms) | 75.8 | 84.0 |
| Compartment Intrusions | Door Opening (Δ mm) | 7.6 | 8.7 |
| | Footrest (mm) | 50.5 | 48.7 |
| | Driver Toepan Left (mm) | 53.3 | 76.7 |
| | Driver Toepan Center (mm) | 61.4 | 113.0 |
| | Driver Toepan Right (mm) | 57.7 | 123.2 |




The baseline with the redesigned Frame shows an increase in intrusion.

**Figure 4.18-191: IIHS Frontal Impact (ODB) – Results**

Substituting the baseline frame with the redesigned frame saved 23.7kg of mass but the test results indicates a reduction in the load capacity of the front rails. With the mass of the vehicle otherwise unchanged, the performance in both FMVSS 208 Frontal Impact and IIHS Frontal Impact (ODB) is degraded. The FMVSS 208 Frontal Impact results show higher intrusions in the driver toepan area, larger dynamic crush which tends to a slightly higher max acceleration late in the event and a less efficient rail buckling mode. The IIHS Frontal Impact (ODB) results show higher intrusions in the footrest, driver toepan and right IP points along with a larger dynamic crush with earlier peak acceleration. Therefore, the redesigned frame installed in the baseline vehicle does not maintain the baseline specifications and is assigned as secondary mass savings.

The bumpers were also included as secondary mass savings as they function with the frame during crash and their performance during the FMVSS 581 Bumper Testing is impacted by the overall vehicle weight. Further analyses may reveal a portion of the mass could be divided between primary and secondary for some of these components, although this analysis was not pursued.

# 5. Supplementary Analyses

## 5.1 Additional Weight Savings Ideas Not Implemented – Overview

During the mass reduction idea generation phase of the project (Step 2 of overall project methodology), numerous mass reduction ideas were generated. For various reasons (e.g. performance degradation risk, implementation readiness risk, unit cost increase, better value ideas “$/kg”), many of the ideas were not selected for the final vehicle solution.

In the Powertrain, Chassis and Trim Evaluation Group, many of the ideas considered were discussed in their respective vehicle system white paper section (Section 4, Mass Reduction and Cost Analyses – Vehicle Systems White Papers). Although not used in the final analysis, some ideas are very exciting and deserve additional discussion.

For the Body and Frame Evaluation Group, many mass reduction iterations and considerations were also developed and assessed. Two major iterations not included in the final vehicle solution were a high strength steel (HSS) intensive body and cargo box iteration and aluminum intensive frame iteration. Although these iterations were not considered prime path, the team did create two alternative vehicle solutions which included these subsystem alternatives. No other subsystem/system component changes were made as part of these iterations. For example the same brake system mass reduction ideas included in the final mass reduction solution were also used in the “HSS Intensive” and “Aluminum Intensive” iterations. In the context of this analysis “Intensive” indicates the majority of components were made from one material type. For example in the HSS Intensive iteration, the majority of the frame structure is made from HSS, with a couple cross-member components made from aluminum.

These two iterations were also used in the development of the final cost curve. In **Table 5.1-1** below the results for the final/primary vehicle solution (aka, Aluminum Intensive

Body and HSS intensive Frame) are shown alongside the HSS Intensive and Aluminum Intensive Body and Frame iterations. For the HSS Intensive and Aluminum Intensive iterations, the NVH counter measures were scaled relative to the final vehicle solution mass reduction. The "HSS Intensive Body and Frame" NVH counter measures equaled 42.1 kg at a cost increase of $126.41. The "Aluminum Intensive Body and Frame" NVH counter measures equaled 52.7 kg at a cost increase of $158.02

In the **Subsections 5.2 (Powertrain, Chassis and Trim)** and **5.3 (Body and Frame)** additional details on alternative mass reduction ideas are presented.

**Table 5.1-1: Vehicle Mass Reduction and Cost Comparison of Three Vehicle Solution Alternatives**

| Item | System ID | Description | Mass Reduction Impact by Vehicle System: Base Mass "kg" | Mass Reduction "kg" (1) | Cost Impact NIDMC "$" (2) | Cost/ Kilogram NIDMC "$/kg" (2) | Cost/ Kilogram NIDMC + Tooling "$/kg" (2) | System Mass Reduction "%" | Vehicle Mass Reduction "%" |
|---|---|---|---|---|---|---|---|---|---|
| 1500 Series Chevrolet Silverado Pick-Up - Aluminum Intensive Body and HSS Intensive Frame (i.e., Final Solution) | | | | | | | | | |
| | | a. Analysis Totals Without NVH Counter Measures | **2454.4** | **560.9** | **-2073.82** | **-3.70** | **-3.69** | **n/a** | **22.9%** |
| | | b. Vehicle NVH Counter Measures (Mass & Cost ) | 0.0 | -50.0 | -150.00 | **n/a** | **na** | **na** | **na** |
| | | c. Analysis Totals With NVH Counter Measures | **2454.4** | **510.9** (Decrease) | **-2223.82** (Increase) | **-4.35** (Increase) | **-4.35** (Increase) | **n/a** | **20.8%** |
| 1500 Series Chevrolet Silverado Pick-Up - HSS Intensive Body and Frame | | | | | | | | | |
| | | a. Analysis Totals Without NVH Counter Measures | **2454.0** | **472.7** | **-1209.00** | **-2.56** | **-2.55** | **n/a** | **19.3%** |
| | | b. Vehicle NVH Counter Measures (Mass & Cost ) | 0.0 | -42.1 | -126.41 | **n/a** | **na** | **na** | **na** |
| | | c. Analysis Totals With NVH Counter Measures | **2454.0** | **430.6** (Decrease) | **-1335.41** (Increase) | **-3.10** (Increase) | **-3.09** (Increase) | **n/a** | **17.5%** |
| 1500 Series Chevrolet Silverado Pick-Up - Aluminum Intensive Body and Frame | | | | | | | | | |
| | | a. Analysis Totals Without NVH Counter Measures | **2454.0** | **590.9** | **-2504.26** | **-4.24** | **-4.23** | **n/a** | **24.1%** |
| | | b. Vehicle NVH Counter Measures (Mass & Cost ) | 0.0 | -52.7 | -158.02 | **n/a** | **n/a** | **n/a** | **n/a** |
| | | c. Analysis Totals With NVH Counter Measures | **2454.0** | **538.2** (Decrease) | **-2662.29** (Increase) | **-4.95** (Increase) | **-4.94** (Increase) | **n/a** | **21.9%** |

(1) Negative value (i.e., **-X.XX** ) represents an increase in mass
(2) Negative value (i.e., **-$X.XX**) represents an increase in cost

## 5.2 Powertrain, Chassis and Trim Evaluation Group Ideas Not Implemented

Replacing cast iron lower control arms with magnesium will result in a mass savings of approximately 5.8 kg per control arm at a cost hit of $8.00 per control arm. General Motors China Advanced Technical Center (ATC) announced in May 2012 that it had successfully cast a prototype magnesium alloy control arm and noted that the part was 30% lighter than a similar part made from aluminum. Although the cost of this change would be $1.38 per kg, which was viable from a cost perspective, the idea was not selected because it is a relatively new technology that caused some concern as to its market readiness for light-duty trucks. Therefore, because of the certainty of forged aluminum control arms in a light-duty truck application, the forged aluminum lower control arms were selected.

Using carbon fiber wheels instead of aluminum was an option. Changing the wheels to carbon fiber will save approximately 6 kg per wheel with an estimated cost increase of $600.00 per wheel. Carbon Revolution already sells carbon fiber wheels to high end sports cars such as the Porsche 911 for approximately $15,000 per set. BMW recently revealed during BMW's Innovation days in Munich that they will manufacture a carbon fiber reinforced plastic (CFRP) wheel for their BMW i3 and i8 electric cars. The wheels, according to Auto Express, will either be all CFRP or will use a CFRP rim with alloy spokes. The full-CFRP wheel is 35% lighter than a forged alloy wheel, the hybrid alloy and CFRP wheel is 25% lighter. With a cost of $100 per kg this idea was not selected due to the high cost. Instead, an ultra-lightweight forged aluminum mono-block wheel was implemented.

With respect to the engine system, 113 ideas were brainstormed for engine lightweighting; 43 of the ideas brainstormed were selected as viable solutions. Reasons for why an idea or ideas were not selected included: greater mass savings would be achieved with another idea, excessive cost, or durability concerns. For example, the racing industry has developed a variety of engine lightweighting and performance enhancing technologies that have value for racing but are cost limited for production lightweighting.

Polyamide engine mounts as a replacement for metal have been proven in passenger car applications. These mounts can save both mass and cost but have yet to be proven in a truck application and therefore were not selected to replace the Silverado stamped steel engine mounts.

Titanium connecting rods have been used to reduce mass and increase performance of high-end production vehicles. Replacing the Silverado's powder metal connecting rod with titanium saves 2.0 kg and increases cost by $101.00 per vehicle. This idea was not selected due to the cost of $50.28 per kg.

Titanium as a replacement for stainless steel in engine valves saves mass and improves performance. Titanium valves applied to the Silverado saves approximately 1 kg at a cost of $28.00. This technology was not selected due to the cost of $9.61 per kg

Aluminum metal matrix composite wrist pins have been used in racing applications as a replacement for steel. Applied to the Silverado this technology saves 0.8 kg at a cost of $48.00 per vehicle. This technology was not selected due to the cost of $25 per kg.

For additional details on mass reduction ideas considered, please refer to the respective vehicle system in Section 4.

### 5.3 Frame and Body Evaluation Group Ideas Not Implemented

As discussed in Section 4, the final vehicle solution contained an aluminum intensive body and high strength steel intensive frame. During the optimization process the team started by investigating more conservative approaches to reducing mass in the Body System Group -A- and Frame Systems by initially focusing on HSS substitution, gauge optimization, tailor rolled blanks, tailor welded blanks, etc. With concerns that the minimum 20% vehicle mass reduction may not be achieved, the team decided to pursue some additional light-weighting alternatives. This included design iterations with significant aluminum use in the cabin and cargo box structures, to more extreme iterations which included the aluminum frame consideration. Additional details on both of these iterations are included below.

### 5.3.1 HSS/AHSS Body Structures (Cabin and Cargo/Box Assemblies)

The HSS Intensive design made significant use of HSS for the cabin, cargo/box assembly pickup and frame assembly. The weight reduction of the HSS intensive vehicle is shown in comparison to the baseline and final solution vehicle in **Table 5.3-1**. In this iteration many of the other subsystems including the closure and bumper subsystems were common with those used in the “Final Solution”. For reference the closure subsystems were all redesigned in aluminum. Further optimization may have been possible with the HSS intensive integration, though because it was removed from the detailed analysis as part of the down-selection process, complete feasibility and optimization was not completed.

The decrease in mass savings, relative to the final solution containing aluminum body structures, was 88.2 kg (80.3 kg w/ NVH counter measure). In terms of impact on overall vehicle mass reduction, 3.3% less mass reduction would be achieved with a HSS body structure versus aluminum body structure. Though financially, the integration of an advance HSS versus aluminum body structure would yield a savings of $888 ($864 w/NVH counter measure).

**Table 5.3-1: Mass and Cost Summary for HSS Intensive Vehicle**

| Current Silverado Models - Mass | | | | Delta Mass | | Delta Cost | | Cost/Kilogram | |
|---|---|---|---|---|---|---|---|---|---|
| System | Baseline Model (kg) | HSS Intensive[1] (kg) | Final Solution[2] (kg) | HSS Intensive[1] (kg) | Final Solution[2] (kg) | HSS Intensive[3] ($) | Final Solution[3] ($) | HSS Intensive[3] ($/kg) | Final Solution[3] ($/kg) |
| BOX ASY PICK-UP | 108.3 | 95.7 | 73.9 | 12.6 | 34.4 | 18.89 | -241.45 | 1.50 | -7.02 |
| FRAME ASY | 242.0 | 211.4 | 218.3 | 30.6 | 23.7 | -43.29 | -54.42 | -1.41 | -2.30 |
| CABIN | 207.2 | 194.6 | 131.8 | 12.6 | 75.4 | -17.73 | -505.28 | -1.41 | -6.70 |
| PANEL FENDER OUTER LH | 14.9 | 11.1 | 7.4 | 3.8 | 7.5 | -2.63 | -19.60 | -0.69 | -2.61 |
| PANEL FENDER OUTER RH | 14.0 | 10.5 | 7.0 | 3.5 | 7.0 | -2.45 | -18.30 | -0.70 | -2.61 |
| Radiator Structure | 12.9 | 8.9 | 7.2 | 4.0 | 5.7 | 3.28 | -10.58 | 0.82 | -1.86 |
| Extra Cabin - Radiator Support | 12.1 | 7.8 | 6.2 | 4.3 | 5.9 | 6.44 | -52.59 | 1.50 | -8.91 |
| Sub-total | 611.4 | 540.0 | 451.8 | 71.4 | 159.6 | -37.49 | -902.22 | -0.53 | -5.65 |
| BUMPER FRONT | 28.5 | 18.6 | 18.6 | 9.9 | 9.9 | -23.88 | -23.88 | -2.41 | -2.41 |
| BUMPER REAR | 19.9 | 13.4 | 13.4 | 6.5 | 6.5 | -46.27 | -46.27 | -7.12 | -7.12 |
| HOOD ASY WITHOUT HINGES | 22.7 | 11.7 | 11.7 | 11.0 | 11.0 | -35.18 | -35.18 | -3.20 | -3.20 |
| DOOR ASY FRONT LH | 29.0 | 18.8 | 18.8 | 10.2 | 10.2 | -59.15 | -59.15 | -5.80 | -5.80 |
| DOOR ASY FRONT RH | 28.9 | 18.8 | 18.8 | 10.1 | 10.1 | -58.57 | -58.57 | -5.80 | -5.80 |
| DOOR ASY REAR LH | 22.0 | 15.0 | 15.0 | 7.0 | 7.0 | -48.53 | -48.53 | -6.93 | -6.93 |
| DOOR ASY REAR RH | 22.2 | 15.0 | 15.0 | 7.2 | 7.2 | -49.91 | -49.91 | -6.93 | -6.93 |
| Cargo Box Gate | 18.8 | 10.2 | 10.2 | 8.6 | 8.6 | -26.35 | -26.35 | -3.06 | -3.06 |
| Sub-total | 192.0 | 121.5 | 121.5 | 70.5 | 70.5 | -347.84 | -347.84 | -4.93 | -4.93 |
| Total | 803.4 | 661.5 | 573.3 | 141.9 | 230.1 | -385.3 | -1250.1 | -2.7 | -5.4 |

1 - "HSS Intensive" iteration consisted of same Powertrain, Chassis and Trim Evaluation Group mass-reduction ideas as in the "Final Solution"
2 - "Final Solution" consisted of HSS Intensive Frame and Aluminum Intensive Body
3 - Negative cost represents a cost increase

### 5.3.2 Aluminum Intensive Frame

To push the mass reduction mass reduction envelop further, the team investigated an "Aluminum Intensive" iteration which looked at the possibility of replacing the steel frame design, mostly comprised of HSS steel (in the final solution), with an aluminum design. Some other minor BIP changes were also made as part of this iteration.

The manufacturing possibilities of an all-aluminum frame were not highly investigated as the cost and short-term feasibility were less appealing than the upgraded HSS version. However the team wanted to understand what the future would look like in terms of weight reduction and costs for an aluminum frame. **Table 5.3-2** presents the additional mass savings and cost impact relative to the baseline (i.e., production stock Silverado) vehicle. The aluminum frame version included many of the same light-weight components as put through in the final solution as shown in the table. It should be noted that the "Aluminum Intensive" iteration was not fully optimized and as such the mass reduction numbers and costs are consider good engineering estimates only.

Looking at the impact of the aluminum frame conversion, an additional 30kg (27.3 kg w/ NVH counter measure) of mass was saved. The Net Incremental Direct Manufacturing Cost impact of the aluminum frame, relative to the HSS version, was nearly $430 ($438.5 w/NVH counter measure).

**Table 5.3-2: Weight and Cost Impact of Aluminum Intensive Iteration**

| | Current Silverado Models - Mass | | | Delta Mass | | Delta Cost | | Cost/Kilogram | |
|---|---|---|---|---|---|---|---|---|---|
| System | Baseline Model (Kg) | Aluminum Intensive[1] (Kg) | Final Solution[2] (kg) | Aluminum Intensive[1] (Kg) | Final Solution[2] (kg) | Aluminum Intensive[3] ($) | Final Solution[3] ($) | Aluminum Intensive[3] ($/kg) | Final Solution[3] ($/kg) |
| BOX ASY PICK-UP | 108.3 | 73.9 | 73.9 | 34.4 | 34.4 | -241.45 | -241.45 | -7.02 | -7.02 |
| FRAME ASY | 242.0 | 184.7 | 218.3 | 57.3 | 23.7 | -466.49 | -54.42 | -8.14 | -2.30 |
| CABIN | 207.2 | 131.8 | 131.8 | 75.4 | 75.4 | -505.28 | -505.28 | -6.70 | -6.70 |
| PANEL FENDER OUTER LH | 14.9 | 9.2 | 7.4 | 5.7 | 7.5 | -29.24 | -19.60 | -5.13 | -2.61 |
| PANEL FENDER OUTER RH | 14.0 | 8.8 | 7.0 | 5.2 | 7.0 | -26.68 | -18.30 | -5.13 | -2.61 |
| Radiator Structure | 12.9 | 7.2 | 7.2 | 5.7 | 5.7 | -10.58 | -10.58 | -1.86 | -1.86 |
| Extra Cabin - Radiator Support | 12.1 | 6.2 | 6.2 | 5.9 | 5.9 | -52.59 | -52.59 | -8.91 | -8.91 |
| Sub-total | 611.4 | 421.8 | 451.8 | 189.6 | 159.6 | -1332.31 | -902.22 | -7.03 | -5.65 |
| BUMPER FRONT | 28.5 | 18.6 | 18.6 | 9.9 | 9.9 | -23.9 | -23.88 | -2.41 | -2.41 |
| BUMPER REAR | 19.9 | 13.4 | 13.4 | 6.5 | 6.5 | -46.3 | -46.27 | -7.12 | -7.12 |
| HOOD ASY WITHOUT HINGES | 22.7 | 11.7 | 11.7 | 11.0 | 11.0 | -35.2 | -35.18 | -3.20 | -3.20 |
| DOOR ASY FRONT LH | 29.0 | 18.8 | 18.8 | 10.2 | 10.2 | -59.1 | -59.15 | -5.80 | -5.80 |
| DOOR ASY FRONT RH | 28.9 | 18.8 | 18.8 | 10.1 | 10.1 | -58.6 | -58.57 | -5.80 | -5.80 |
| DOOR ASY REAR LH | 22.0 | 15.0 | 15.0 | 7.0 | 7.0 | -48.5 | -48.53 | -6.93 | -6.93 |
| DOOR ASY REAR RH | 22.2 | 15.0 | 15.0 | 7.2 | 7.2 | -49.9 | -49.91 | -6.93 | -6.93 |
| Cargo Box Gate | 18.8 | 10.2 | 10.2 | 8.6 | 8.6 | -26.4 | -26.35 | -3.06 | -3.06 |
| Sub-total | 192.0 | 121.5 | 121.5 | 70.5 | 70.5 | -347.8 | -347.84 | -4.93 | -4.93 |
| Total | 803.4 | 543.3 | 573.3 | 260.1 | 230.1 | -1680.2 | -1250.1 | -6.5 | -5.4 |

1 - "Aluminum Intensive" integration consisted of same Powertrain, Chassis and Trim Evaluation Group mass-reduction ideas as in the "Final Solution"
2 - "Final Solution" consisted of HSS Intensive Frame and Aluminum Intensive Body
3 - Negative cost represents a cost increase

## 5.4 Alternative Materials

With further development, alternative materials have the potential for broader inclusion in body, chassis, and powertrain component weight reduction. Some future options identified include:

**Magnesium (Mg)**: One of the positive attributes of Magnesium alloys is their high strength to weight ratios. A similar test of replacing steel materials with magnesium materials on the front module of the Silverado revealed approximately 57.3% weight savings with 100% cost increase. The use of magnesium as a viable alternative will be a consideration in future research. Another area in which magnesium has the potential to be used is in powertrain components [53].

**Carbon Fiber**: The proposition of composite materials utilizing carbon fiber is one of the emerging ideas in building lightweight vehicles. Currently, the use of fiber-composite materials for supporting body parts has been limited to special series, as well as premium and racing models[54]. Assuming a positive cost impact due to an improvement in efficiency, continued research into using composite materials for auto body parts is worthwhile.

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53 Jurgen Leohold, Pathways for a Sustainable Automotive Future, Volkswagen Conference Proceedings, May 2009.

54 Gundolf Kopp, Strategies and methods for multi-material structure and concept developments, German Aerospace Center (DLR), Volkswagen Conference Proceedings, May 2009.

**Long-Fiber Reinforced Thermoplastics (LFT)**: Another candidate for alternative materials is long-fiber reinforced thermoplastics. Today, most LFT end-products are produced for the automobile industry[55]. These molded parts include body panels, sound shields, front-end assemblies, structural body parts, truck panels, housings, doors, tailgates, and fender (wing) sections. LFT could be applied on the aforementioned parts of the Silverado.

**Aluminum Metal Matrix Composite (Al MMC)**: Utilizing high-strength ceramic particles uniformly distributed throughout an aluminum alloy matrix creates a material with one-third the density of cast iron but with comparable strength and wear resistance. Components requiring stiff, lightweight alloys that need to accelerate and change direction at high frequency such as pistons and wrist pins leverage the most benefit from aluminum MMC. Increased tool wear makes machining this material difficult. Selective reinforcement or the use of aluminum MMC only in high-stress areas of a part can minimize cost. Continued development of this option would provide additional benefits for lightweighting.

# 6. Conclusion, Recommendations and Acknowledgements

## 6.1 Conclusion and Recommendations

The primary project objective was to determine the minimum cost per kilogram for various levels of vehicle mass reduction of a light-duty pickup truck, up to and possibly beyond 20%. A maximum 10% increase in total direct manufacturing cost limit was placed as a soft constraint in order to focus the study on more realistic ideas for near-term adoption. The selection criteria for the truck chosen for evaluation specified a mainstream vehicle in terms of design and manufacturing, with a substantial market share in the North American light-duty truck market. Selecting a high-volume, mainstream vehicle increased the probability that the ideas generated and their associated costs would be applicable to other pickups trucks within the same market segment.

Key elements of the scope of work included the following:

- Select a mainstream pickup truck, available in the 2011 calendar year, with significant market share in North America. Trucks for consideration should include the Ford F150, Dodge Ram 1500, Chevrolet Silverado 1500, and Nissan Titan.

55 Lars Fredrik Berg, Polymer technologies for innovative light weight vehicle structures, Volkswagen Conference Proceedings, May 2009.

- Select mass reduction ideas that use advanced materials, designs, manufacturing and assembly processes which will likely be available in the 2020-2025 timeframe.
- All direct mass reduction of components (e.g., design and/or material alternatives) as well as mass reduction of components via mass compounding (also referred to as secondary mass savings) are considered viable options. For this project, mass reduction compounding refers to the reduction of mass of a given component as the result of a reduction in the mass of one or several other components.
- Select mass reduction ideas that are production feasible and provide the best value in terms of fixed and variable costs (i.e., maximum 10% vehicle direct manufacturing cost increase).
- Maintain (or improve) the function and performance of the production stock vehicle systems in terms of safety, fuel economy, vehicle utility/performance (e.g., towing, acceleration), NVH (noise, vibration, and harshness), durability, ergonomics, aesthetics, manufacturability, and serviceability.
- Utilize CAE tools as appropriate when comparing baseline vehicle functionalities to the light-weighted design, such as for safety, NVH, powertrain performance, towing, durability, etc.
- Provide comprehensive incremental cost calculations for the mass-reduced vehicle relative to the production stock vehicle, including both detailed direct manufacturing costs (i.e., material, labor and manufacturing overhead) and indirect costs (i.e., end-item scrap, selling, general, and administrative [SG&A], profit and engineer, design, and testing [ED&T]).
- Develop incremental tooling cost calculations for the mass-reduced vehicle relative to the production stock vehicle.
- The tools and processes to model direct manufacturing costs should be detailed and representative of those used by OEMs and suppliers in the automotive industry.
- Determine material utilization mix (e.g., steel, plastic, aluminum, magnesium) of production stock vehicle with respect to mass-reduced vehicle.

The mass reduction and cost analysis team was successful in achieving the established project objectives. Within the scope of this project, our team had the advantage of focusing only on mass reduction, maintaining all other vehicle attributes. Conversely, within the OEM scope of vehicle product development, mass-consciousness is just one of many vehicle attributes to which engineers and designers must pay special attention during a new development project. Furthermore, mass reduction is treated passively historically; that is, product engineers must maintain status quo in terms of component and assembly target weights unless there are specific vehicle weight concerns. However, special attention has been given more recently to mass reduction. Examples of other active full-vehicle mass reduction include the launch of the 2013 light-weight Cadillac ATS and the recent launch of the 2015 Ford F150 aluminum intensive pickup truck.

Many OEMs as well are actively pursuing light-weighing in traditionally heavier vehicle systems, including body-in-white, suspension, brakes, and body interior.

The hope is this report provides a list of feasible and affordable mass reduction ideas for several of the vehicle systems, facilitating the integration of additional lightweighting initiatives by OEM and suppliers. The advantage of secondary mass-saving was also an important point stressed in the analysis illustrating that through holistic vehicle mass reduction efforts, additional vehicle mass reduction (≈4%) can be achieved at no additional cost at 20% vehicle mass reduction.

Many of the ideas presented are feasible now. The team believes that all ideas selected in the final mass-reduced vehicle solution (i.e., 20.8% or 510.9 kg mass-reduced vehicle) could be viable high production solutions in the 2020-2025 timeframe. There were also many ideas presented yet not incorporated in the final solution that may develop into more affordable mass reduction ideas by this timeframe.

For the Powertrain, Chassis, and Trim Evaluation Group, the team successfully generated mass reduction concepts totaling 13.4% vehicle mass reduction. Key vehicle systems contributing to the 13.4% included Suspension (4.3%), Brakes (1.9%), Engine (1.3%), Transmission (1.6%), and Body System Group “B” - Body Interior (1.4%).

The team focused a great deal of its effort on ensuring the mass reduction ideas were feasible from product, manufacturing, and timeframe standpoints. To make certain this was the case, the mass reduction ideas selected for the analysis generally met one of the following primary criteria:

- Existing in current high-volume automotive production
- Existing in current low-volume automotive production
- From non-conventional, non-production, mass-production automotive market (e.g., racing, after-market)
- Currently under development by suppliers (e.g., material suppliers, Tier 1 suppliers) with a high potential for success
- Ideas employed in non-automotive industries

The team did its best to validate mass reduction concepts through the use of advance CAE tools within the project funding and timing limits. The majority of this effort was placed on safety-related systems such as the body and frame vehicle systems. For the Powertrain, Chassis and Trim Evaluation Group, the team conducted basic engineering assessments, primarily in the form of reverse engineering, to determine the feasible amount of mass reduction. A combination of automotive supplier support, surrogate benchmark data (i.e., purchased hardware and various benchmark databases), and published literature facilitated the transfer of mass reduction materials, designs, and manufacturing methods to the Chevrolet Silverado production stock components. Details on where the mass reduction ideas came from, how they were applied, and what engineering assessments were made in incorporating the ideas can be found in the various vehicle systems throughout Section 4.

The Net Incremental Direct Manufacturing Cost (NIDMC) impact of the Powertrain, Chassis, and Trim Evaluation Group was an increase of approximately $824, resulting in average cost per kg of $2.50.

For the Body and Frame Evaluation Group, the approach of creating and validating a Silverado like baseline production model from which all mass reduction updates could be validated was considered a robust approach by the team. The baseline CAE model was validated using actual production vehicle test data which included both NVH tests and cash worthiness tests (crash data from NHTSA). The following tests provided the team with confidence that the CAE models were representative in performance to a production such as the 1500 Silverado.

**NVH Tests:**

- Frame – Static Bending and Static Torsion
- Cabin – Static Bending and Static Torsion
- Body On Frame – Static Bending and Static Torsion

**Crashworthiness Load Case Tests - Full Vehicle**

- FMVSS 208 - 35 mph flat frontal crash (US NCAP)
- FMVSS 214 - 38.5 mph MDB side impact (US SINCAP)
- FMVSS 214 - 20 mph 5th Percentile pole side impact

Additional crash worthiness tests were added in order to support the assessment of the baseline vehicle to the various mass-reduced iterations. These additional tests included:

- IIHS - 40 mph  ODB frontal crash
- IIHS -31 mph MDB side impact
- FMVSS 301 – 50 mph MDB rear impact
- FMVSS 261a – roof crush
- FMVSS 581 - bumper impact

Using various crash comparison measurements (e.g., vehicle pulse, time-to-zero velocity, deformation modes, sheet-metal intrusion, etc.), the mass-reduced body and frame structures were compared to the baseline model to ensure that crash performance integrity was maintained with the implementation of the mass reduction concepts. The detailed analysis conducted by EDAG supported that the body and frame mass reduction is a viable means to reduce the overall vehicle weight without degrading performance and safety. This is important since, in the case of the Chevrolet Silverado, the Body System Group -A- and Frame System contributed 8.4% (207.1 kg) and 1.0% (23.7 kg) respectively to the overall vehicle mass reduction.

Apart from improving weight saving potential, the light weighting trade off process with global performance and cost impact was investigated. The study was visualized by plotting each of the characteristics on a spider chart as shown in Error! Reference source ot found..

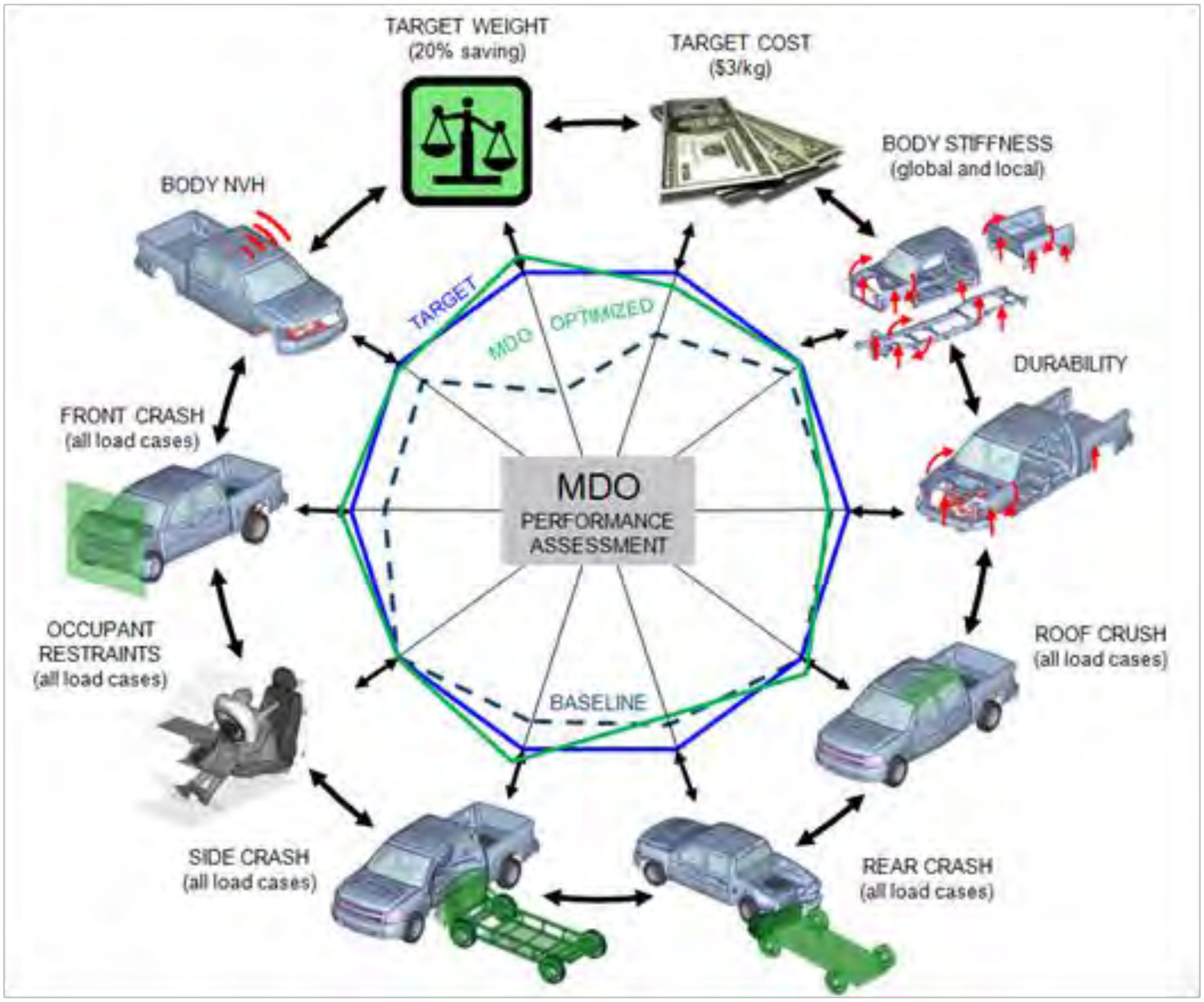


**Figure 6.1-1**: **Lightweighting Trade-off Trend**
*(Source: FEV, Inc.)*

In **Figure 6.1-1**: Lightweighting Trade-off Trend the blue line represents the light weighting target values, the green line represents the achieved values (normalized) from MDO (Multidisciplinary Design Optimization), and the dotted line represents the baseline values for each of the characteristics. As discussed in this study, it is observed that the vehicle weight reduction (20.8%) is exceeding the target (20%) but with higher cost ($4.35 per kg versus $3.00 per kg target), this is shown in the chart with the green line below the blue target value on target cost.

It is also noted that the light weighted vehicle performance is shown to achieve above the target levels for a number of areas on the chart in the roof, side and front loadcases. It should be noted that, occupant safety variants were not directly investigated as part of full vehicle scenarios. The occupant safety performance shown in the above chart is an assumption based on normalized structural performance variants. The chart also reveals that the rear impact performance analysis is below the expected target for both the baseline and the light-weighted design.

The front crash pulse in the optimized design was found to be higher than the crash pulse in the baseline vehicle. The difference can be remediated by improved restraint systems and air bag deployment timing.

From the cost perspective, the Body System Group -A- had the largest overall cost impact due to the high use of aluminum in the cabin, cargo box, and closure subsystems. The Net Incremental Direct Manufacturing Cost (NIDMC) increase was near $1,200 per vehicle ($5.77 per kg). The Frame System made use of advanced HSS (high strength steel), with two aluminum cross members, for a more conservative weight reduction, but also at a much more conservative cost. The NIDMC increase was calculated to be $54, or $2.30 per kg.

The Body System Group -A- and Frame System included some smaller items in addition to the primary components evaluated by EDAG. Thus, there are some very minor differences in recorded mass and costs in comparison to those included in **Section 4.17**: **Body and Frame Systems**, which only includes the EDAG work.

Combining the results of all vehicle systems evaluated (i.e., results for both evaluation groups), a total mass reduction of 560.9 kg was achieved at NIDMC increase of $2,074 per vehicle. This translates to an average cost per kilogram of $3.70. These costs are considered mature, mass-production costs exclusive of any OEM indirect costs (e.g., corporate overhead, R&D, tooling, profit, etc.). When the tooling impact was considered (incremental savings in tooling of $7.3M over the production stock/baseline Silverado), the cost per kg decreased by approximately $0.01 per kg, resulting in an NIDMC increase of $3.69 per kg.

Within the report the team addresses the concerns of evaluating components and assemblies without the ability to consider all potential negative assembly, subsystem, and system interactions associated with mass reduction. Potential changes may be required for tuning out NVH issues, increasing stiffness, and/or making component adjustment for vehicle dynamics. To protect for these countermeasures, the team added 50 kilograms of mass, and $150 back into the analysis results. Thus, the final vehicle mass reduction results, including allowance for counter measures, were 510.9kg at a cost of $2,224 /vehicle ($4.353 per kg and $4.346 per kg with tooling).

The FEV, Munro, and EDAG team view mass reduction as a viable and cost-competitive methodology for improving fuel economy and reducing greenhouse gas (GHG) emissions in addition to other potential vehicle technologies. This advanced preliminary engineering assessment indicates mass reduction can be implemented on a light-duty pickup truck without diminishing the function and performance of the vehicle (in this case, a 2011 Chevrolet Silverado). As such, the team recommends the continued, industry-wide engineering efforts and corresponding investments into mass reduction research and development in an effort to meet the fuel economy and GHG emission requirements of tomorrow.

## 6.2 Acknowledgments

The EPA, in order to create a thorough, transparent, and robust study, invited various government entities to participate and/or provide feedback during the study duration.

The EPA also acknowledges the following industries, partners, and reviewers for contributions and input made within this report:

- American Chemistry Council
- Aluminum Association
- American Iron and Steel Institute
- International Magnesium  Association and Suppliers
- American Foundry Society
- USCAR-USAMP High Integrity Magnesium Automotive Casting Project
- T1 Component Suppliers
- Air Resources Board (ARB)
- International Council on Clean Transportation (ICCT)
- National Highway Transportation Safety Administration (NHTSA)
- OEM Feedback
- A2Mac1
- The various supplies referenced and credited throughout the report

Participating and partnering financially in this study with the EPA was the International Council on Clean Transportation (ICCT).

A white paper project review presentation and draft final report have been provided to the National Highway Transportation Safety Administration (NHTSA) for comments. NHTSA was also periodically informed about the project progress during the EPA, DOE, DOT and CARB working group meeting.

ERG was subcontracted by the EPA to conduct the peer review for this project.  A special thank you to the peer review team for conducting a thorough review of the report, providing valuable recommendations on enhancing the overall analysis and final report. The peer review team included:

- Sujit Das, MS, MBA  Oak Ridge National Laboratory
- John Fillion, MS, Private Consultant (formerly Chrysler, LLC)
- Douglas A Richman, MBA, Kaiser Aluminum Corporation
- Srdjan Simunovic, PhD, Oak Ridge National Laboratory
- Mukul K. Verma, Ph.D, University of Alabama at Birmingham

# 7. Appendix

## 7.1 System Level Cost Model Analysis Templates (CMATs)

### 7.1.1 Vehicle System

**Table 7.1-1: Vehicle System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | BASE TECHNOLOGY GENERAL PART INFORMATION: | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| 1 | | 01 Engine | 137.47 | 21.96 | 100.72 | 260.16 | 6.54 | 22.27 | 19.26 | 5.14 | 53.21 | - | 313.36 | - | 30,953.62 | - |
| 2 | | 02 Transmission | 325.40 | 65.27 | 119.24 | 509.91 | 3.98 | 39.82 | 41.31 | 16.01 | 101.12 | - | 611.03 | - | 21,835.00 | - |
| 3 | | 03 Body | 1,492.27 | 96.29 | 274.74 | 1,863.29 | 2.79 | 41.38 | 34.41 | 9.05 | 87.62 | - | 1,950.91 | - | 16,958.33 | - |
| | | Body System Group -A- ( Body Sheetmetal) | 1,149.08 | 36.29 | 108.39 | 1,293.76 | 0.11 | 1.40 | 1.29 | 0.38 | 1,296.94 | - | 1,296.94 | - | - | - |
| | | Body System Group -B- (Body Interior) | 278.23 | 54.79 | 80.90 | 413.92 | 1.91 | 30.50 | 23.95 | 5.23 | 475.51 | - | 475.51 | - | 16,958 | - |
| | | Body System Group -C- (Body Exterior Trim) | 49.53 | 1.89 | 3.59 | 55.02 | 0.30 | 4.75 | 3.77 | 0.76 | 64.60 | - | 64.60 | - | - | - |
| | | Body System Group -D- (Glazing & Body Mechatronics) | 15.43 | 3.31 | 81.85 | 100.59 | 0.47 | 4.74 | 5.40 | 2.66 | 113.87 | - | 113.87 | - | - | - |
| 4 | | 04 Suspension | 608.17 | 83.72 | 242.96 | 934.85 | 4.71 | 46.24 | 51.70 | 24.98 | 127.63 | - | 1,062.49 | - | 8,598.92 | - |
| 5 | | 05 Driveline | 168.70 | 32.36 | 104.45 | 305.52 | 3.13 | 26.48 | 25.05 | 7.85 | 62.51 | - | 368.03 | - | 1,431.25 | - |
| 6 | | 06 Brakes | 132.86 | 21.22 | 85.60 | 239.68 | 1.29 | 14.75 | 15.11 | 6.60 | 37.75 | - | 277.43 | - | 10,345.86 | - |
| 7 | | 07 Frame and Mounting | 479.02 | - | - | 479.02 | - | - | - | - | - | - | 479.02 | - | - | - |
| 8 | | 09 Exhaust | 31.13 | 1.67 | 4.32 | 37.12 | 0.24 | 3.24 | 2.91 | 0.85 | 7.24 | - | 44.35 | - | - | - |
| 9 | | 10 Fuel | 131.07 | 3.13 | 19.16 | 153.36 | 0.54 | 7.58 | 6.58 | 2.37 | 17.07 | - | 170.43 | - | 3,004.25 | - |
| 10 | | 11 Steering | 151.24 | 38.50 | 47.54 | 237.27 | 2.32 | 20.72 | 23.12 | 12.88 | 59.04 | - | 296.32 | - | 2,366.50 | - |
| 11 | | 12 Climate Control | 17.91 | 3.84 | 20.23 | 41.98 | 0.32 | 3.86 | 3.83 | 1.30 | 9.31 | - | 51.29 | - | - | - |
| 12 | | 13 Info, Gage & Warning Device | 2.77 | 0.54 | 1.77 | 5.08 | 0.03 | 0.44 | 0.34 | 0.07 | 0.87 | - | 5.96 | - | 519.90 | - |
| 13 | | 14 Electrical Power Supply | 23.21 | 6.51 | 6.51 | 36.23 | 0.10 | 1.66 | 1.23 | 0.35 | 3.33 | - | 39.56 | - | 1,429.57 | - |
| 14 | | 15 In-Vehicle Entertainment | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 15 | | 17 Lighting | 6.36 | 1.15 | 2.80 | 10.31 | 0.05 | 0.48 | 0.55 | 0.27 | 1.34 | - | 11.65 | - | - | - |
| 16 | | 18 Electrical Distribution & Electrical Control | 95.83 | 0.67 | 1.13 | 97.63 | 0.41 | 8.03 | 5.41 | 0.72 | 14.57 | - | 112.20 | - | 318.50 | - |
| 17 | | 19 Electronic Features | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | SUBSYSTEM ROLL-UP | 3,803.41 | 376.83 | 1,031.17 | 5,211.41 | 26.44 | 236.94 | 230.80 | 88.43 | 582.61 | - | 5,794.02 | - | 97,761.69 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| 1 | 01 Engine | | 196.46 | 50.66 | 108.32 | 355.44 | 4.62 | 20.53 | 19.72 | 6.85 | 51.72 | - | 407.16 | - | 13,989.61 | - |
| 2 | 02 Transmission | | 395.10 | 61.15 | 125.37 | 583.64 | 6.17 | 48.63 | 50.17 | 18.99 | 123.95 | - | 707.60 | - | 22,932.15 | - |
| 3 | 03 Body | | 2,649.80 | 127.00 | 400.22 | 3,177.02 | 2.86 | 43.82 | 35.59 | 9.52 | 91.79 | - | 3,267.90 | - | 19,663.00 | - |
| | | Body System Group -A- ( Body Sheetmetal) | 2,207.45 | 70.43 | 210.83 | 2,488.70 | 0.10 | 1.33 | 1.23 | 0.36 | 3.02 | - | 2,491.73 | - | - | - |
| | | Body System Group -B- (Body Interior) | 381.05 | 50.71 | 104.40 | 536.16 | 2.01 | 33.30 | 25.47 | 5.81 | 66.58 | - | 602.74 | - | 19,663 | - |
| | | Body System Group -C- (Body Exterior Trim) | 47.89 | 1.65 | 3.15 | 52.69 | 0.29 | 4.55 | 3.61 | 0.73 | 9.18 | - | 61.86 | - | - | - |
| | | Body System Group -D- (Glazing & Body Mechatronics) | 13.42 | 4.21 | 81.84 | 99.47 | 0.46 | 4.64 | 5.29 | 2.62 | 13.01 | - | 111.57 | - | - | - |
| 4 | 04 Suspension | | 678.70 | 101.88 | 292.23 | 1,072.82 | 5.51 | 52.08 | 58.46 | 28.53 | 144.57 | - | 1,217.39 | - | 9,970.45 | - |
| 5 | 05 Driveline | | 126.36 | 38.71 | 110.22 | 275.28 | 1.86 | 23.65 | 22.17 | 7.07 | 54.74 | - | 330.01 | - | 409.10 | - |
| 6 | 06 Brakes | | 237.75 | 26.10 | 99.69 | 363.54 | 3.49 | 22.91 | 25.08 | 11.33 | 62.81 | - | 426.35 | - | 19,210.04 | - |
| 7 | 07 Frame and Mounting | | 533.44 | - | - | 533.44 | - | - | - | - | - | - | 533.44 | - | - | - |
| 8 | 09 Exhaust | | 44.45 | 0.61 | 3.26 | 48.31 | 0.32 | 4.43 | 3.89 | 1.09 | 9.73 | - | 58.04 | - | - | - |
| 9 | 10 Fuel | | 121.50 | 2.91 | 18.15 | 142.57 | 0.51 | 7.02 | 6.17 | 2.25 | 15.94 | - | 158.51 | - | 1,005.70 | - |
| 10 | 11 Steering | | 201.50 | 67.30 | 77.53 | 346.32 | 3.64 | 33.56 | 37.90 | 22.37 | 97.46 | - | 443.78 | - | 2,620.50 | - |
| 11 | 12 Climate Control | | 14.41 | 4.32 | 10.93 | 29.67 | 0.25 | 2.77 | 2.86 | 1.04 | 6.91 | - | 36.58 | - | - | - |
| 12 | 13 Info, Gage & Warning Device | | 2.54 | 0.53 | 1.43 | 4.51 | 0.02 | 0.39 | 0.31 | 0.06 | 0.79 | - | 5.30 | - | 376.10 | - |
| 13 | 14 Electrical Power Supply | | 119.32 | 37.92 | 39.03 | 196.27 | 0.44 | 8.24 | 5.79 | 1.55 | 16.02 | - | 212.29 | - | 243.62 | - |
| 14 | 15 In-Vehicle Entertainment | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 15 | 17 Lighting | | 9.43 | 0.61 | 2.04 | 12.08 | 0.06 | 0.56 | 0.64 | 0.32 | 1.57 | - | 13.65 | - | - | - |
| 16 | 18 Electrical Distribution & Electrical Control | | 42.28 | (4.33) | 6.14 | 44.09 | 0.19 | 3.64 | 2.49 | 0.35 | 6.66 | - | 50.75 | - | 90.13 | - |
| 17 | 19 Electronic Features | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | SUBSYSTEM ROLL-UP | 5,373.05 | 515.38 | 1,294.54 | 7,184.99 | 29.93 | 272.22 | 271.23 | 111.30 | 684.67 | - | 7,868.74 | - | 90,510.38 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| 1 | | 01 Engine | (58.99) | (28.70) | (7.59) | (95.29) | 1.92 | 1.74 | (0.46) | (1.71) | 1.49 | - | (93.80) | - | 16,964.01 | - |
| 2 | | 02 Transmission | (69.70) | 4.11 | (6.13) | (73.73) | (2.19) | (8.81) | (8.85) | (2.98) | (22.83) | - | (96.57) | - | (1,097.15) | - |
| 3 | | 03 Body | (1,157.53) | (30.72) | (125.48) | (1,313.73) | (0.08) | (2.44) | (1.18) | (0.47) | (4.17) | - | (1,316.99) | - | (2,704.67) | - |
| | | Body System Group -A- ( Body Sheetmetal) | (1,058.36) | (34.14) | (102.44) | (1,194.94) | 0.01 | 0.06 | 0.06 | 0.02 | 1,293.92 | - | (1,194.79) | - | - | - |
| | | Body System Group -B- (Body Interior) | (102.81) | 4.08 | (23.50) | (122.23) | (0.10) | (2.80) | (1.51) | (0.58) | 408.93 | - | (127.23) | - | (2,705) | - |
| | | Body System Group -C- (Body Exterior Trim) | 1.64 | 0.24 | 0.45 | 2.33 | 0.01 | 0.20 | 0.16 | 0.03 | 55.42 | - | 2.73 | - | - | - |
| | | Body System Group -D- (Glazing & Body Mechatronics) | 2.01 | (0.90) | 0.01 | 1.12 | 0.01 | 0.10 | 0.11 | 0.05 | 100.86 | - | 2.30 | - | - | - |
| 4 | | 04 Suspension | (70.53) | (18.16) | (49.27) | (137.96) | (0.80) | (5.84) | (6.75) | (3.55) | (16.94) | - | (154.90) | - | (1,371.54) | - |
| 5 | | 05 Driveline | 42.34 | (6.34) | (5.76) | 30.23 | 1.27 | 2.84 | 2.88 | 0.78 | 7.77 | - | 38.01 | - | 1,022.15 | - |
| 6 | | 06 Brakes | (104.90) | (4.87) | (14.09) | (123.86) | (2.20) | (8.16) | (9.97) | (4.73) | (25.06) | - | (148.92) | - | (8,864.18) | - |
| 7 | | 07 Frame and Mounting | (54.42) | - | - | (54.42) | - | - | - | - | - | - | (54.42) | - | - | - |
| 8 | | 09 Exhaust | (13.32) | 1.06 | 1.06 | (11.19) | (0.08) | (1.19) | (0.98) | (0.24) | (2.49) | - | (13.69) | - | - | - |
| 9 | | 10 Fuel | 9.57 | 0.22 | 1.01 | 10.80 | 0.03 | 0.56 | 0.41 | 0.12 | 1.12 | - | 11.92 | - | 1,998.55 | - |
| 10 | | 11 Steering | (50.25) | (28.80) | (29.99) | (109.05) | (1.32) | (12.85) | (14.77) | (9.49) | (38.42) | - | (147.46) | - | (254.00) | - |
| 11 | | 12 Climate Control | 3.50 | (0.49) | 9.30 | 12.31 | 0.08 | 1.09 | 0.96 | 0.26 | 2.40 | - | 14.71 | - | - | - |
| 12 | | 13 Info, Gage & Warning Device | 0.23 | 0.01 | 0.34 | 0.57 | 0.00 | 0.05 | 0.03 | 0.00 | 0.09 | - | 0.66 | - | 143.80 | - |
| 13 | | 14 Electrical Power Supply | (96.12) | (31.40) | (32.51) | (160.04) | (0.35) | (6.57) | (4.57) | (1.20) | (12.69) | - | (172.73) | - | 1,185.96 | - |
| 14 | | 15 In-Vehicle Entertainment | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 15 | | 17 Lighting | (3.07) | 0.54 | 0.76 | (1.77) | (0.01) | (0.08) | (0.09) | (0.05) | (0.23) | - | (2.00) | - | - | - |
| 16 | | 18 Electrical Distribution & Electrical Control | 53.55 | 5.00 | (5.00) | 53.54 | 0.22 | 4.39 | 2.92 | 0.37 | 7.90 | - | 61.44 | - | 228.38 | - |
| 17 | | 19 Electronic Features | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | SUBSYSTEM ROLL-UP | (1,569.63) | (138.54) | (263.38) | (1,973.58) | (3.49) | (35.27) | (40.43) | (22.87) | (102.06) | - | (2,074.72) | - | 7,251.31 | - |

### 7.1.2 Engine System

**Table 7.1-2: Engine System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | **01 Engine System** | | | | | | | | | | | | | | |
| 1 | | | 02 Engine Frames, Mounting, and Brackets Subsystem | 5.43 | 0.04 | 0.09 | 5.55 | 0.04 | 0.51 | 0.52 | 0.25 | 1.32 | - | 6.87 | - | 701.03 | - |
| 2 | | | 03 Crank Drive Subsystem | 18.91 | 4.04 | 31.68 | 54.63 | 0.39 | 4.89 | 4.62 | 1.40 | 11.29 | - | 65.92 | - | 319.00 | - |
| 3 | | | 04 Counter Balance Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 05 Cylinder Block Subsystem | 18.63 | 5.45 | 13.92 | 38.00 | 1.37 | 3.33 | 2.94 | 0.90 | 8.54 | - | 46.54 | - | 3,787.40 | - |
| 5 | | | 06 Cylinder Head Subsystem | 7.11 | 0.98 | 4.62 | 12.70 | 0.45 | 1.06 | 0.70 | 0.09 | 2.30 | - | 15.00 | - | 7,252.98 | - |
| 6 | | | 07 Valvetrain Subsystem | 0.68 | 0.29 | 0.74 | 1.71 | 0.01 | 0.15 | 0.12 | 0.03 | 0.31 | - | 2.02 | - | 194.60 | - |
| 7 | | | 08 Timing Drive Subsystem | 4.86 | 0.22 | 1.71 | 6.79 | 0.24 | 0.59 | 0.47 | 0.10 | 1.40 | - | 8.19 | - | 1,551.80 | - |
| 8 | | | 09 Accessory Drive Subsystem | 1.32 | 0.81 | 2.01 | 4.14 | 0.07 | 0.36 | 0.31 | 0.08 | 0.83 | - | 4.97 | - | 512.20 | - |
| 9 | | | 10 Air Intake Subsystem | 1.48 | 0.04 | 0.04 | 1.56 | 0.00 | 0.07 | 0.05 | 0.01 | 0.14 | - | 1.70 | - | 252.80 | - |
| 10 | | | 11 Fuel Induction Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | | | 12 Exhaust Subsystem | 23.79 | 2.55 | 6.87 | 33.21 | 1.17 | 2.91 | 2.30 | 0.47 | 6.85 | - | 40.06 | - | - | - |
| 12 | | | 13 Lubrication Subsystem | 17.35 | 3.42 | 20.26 | 41.03 | 1.33 | 3.57 | 2.79 | 0.55 | 8.23 | - | 49.26 | - | 2,981.15 | - |
| 13 | | | 14 Cooling Subsystem | 20.21 | 3.30 | 14.45 | 37.96 | 0.81 | 3.07 | 3.06 | 1.01 | 7.95 | - | 45.91 | - | 8,874.65 | - |
| 14 | | | 15 Induction Air Charging Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 15 | | | 16 Exhaust Gas Re-circulation Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 16 | | | 17 Breather Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 17 | | | 60 Engine Management, Engine Electronic, Electrical Subsystem | 4.32 | 0.10 | 0.14 | 4.56 | 0.02 | 0.37 | 0.25 | 0.03 | 0.68 | - | 5.24 | - | 655.20 | - |
| 18 | | | 70 Accessory Subsystems (Start Motor, Generator, etc.) | 13.39 | 0.73 | 4.19 | 18.31 | 0.64 | 1.39 | 1.13 | 0.22 | 3.37 | - | 21.68 | - | 3,870.80 | - |
| | | | SUBSYSTEM ROLL-UP | 137.47 | 21.96 | 100.72 | 260.16 | 6.54 | 22.27 | 19.26 | 5.14 | 53.21 | - | 313.36 | - | 30,953.62 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | **01 Engine System** | | | | | | | | | | | | | | |
| 1 | | | 02 Engine Frames, Mounting, and Brackets Subsystem | 4.66 | 0.24 | 0.21 | 5.10 | 0.04 | 0.48 | 0.47 | 0.22 | 1.21 | - | 6.31 | - | 920.34 | - |
| 2 | | | 03 Crank Drive Subsystem | 12.34 | 5.09 | 30.32 | 47.75 | 0.48 | 4.62 | 4.60 | 1.42 | 11.12 | - | 58.87 | - | 805.50 | - |
| 3 | | | 04 Counter Balance Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 05 Cylinder Block Subsystem | 6.74 | 4.31 | 19.85 | 30.89 | 1.13 | 1.93 | 1.80 | 0.64 | 5.50 | - | 36.39 | - | 2,743.20 | - |
| 5 | | | 06 Cylinder Head Subsystem | 2.60 | 0.47 | 1.13 | 4.20 | 0.04 | 0.47 | 0.44 | 0.11 | 1.05 | - | 5.25 | - | 657.00 | - |
| 6 | | | 07 Valvetrain Subsystem | (0.00) | 0.57 | 0.71 | 1.28 | 0.02 | 0.12 | 0.09 | 0.02 | 0.24 | - | 1.52 | - | 1,065.00 | - |
| 7 | | | 08 Timing Drive Subsystem | 7.96 | 0.20 | 0.95 | 9.11 | 0.05 | 0.76 | 0.60 | 0.12 | 1.53 | - | 10.64 | - | 52.56 | - |
| 8 | | | 09 Accessory Drive Subsystem | 2.54 | 0.40 | 0.59 | 3.53 | 0.02 | 0.32 | 0.29 | 0.08 | 0.71 | - | 4.24 | - | 1,837.35 | - |
| 9 | | | 10 Air Intake Subsystem | 1.54 | 0.06 | 0.34 | 1.93 | 0.01 | 0.14 | 0.12 | 0.04 | 0.31 | - | 2.24 | - | 115.00 | - |
| 10 | | | 11 Fuel Induction Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | | | 12 Exhaust Subsystem | 36.04 | 12.01 | 12.01 | 60.06 | - | - | - | - | - | - | 60.06 | - | - | - |
| 12 | | | 13 Lubrication Subsystem | 26.88 | 3.23 | 19.72 | 49.84 | 1.61 | 4.35 | 3.45 | 0.70 | 10.11 | - | 59.95 | - | 2,391.05 | - |
| 13 | | | 14 Cooling Subsystem | 76.62 | 23.52 | 19.50 | 119.64 | 0.58 | 5.80 | 6.59 | 3.25 | 16.22 | - | 135.86 | - | 912.50 | - |
| 14 | | | 15 Induction Air Charging Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 15 | | | 16 Exhaust Gas Re-circulation Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 16 | | | 17 Breather Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 17 | | | 60 Engine Management, Engine Electronic, Electrical Subsystem | 2.67 | 0.03 | 0.11 | 2.80 | 0.02 | 0.21 | 0.19 | 0.05 | 0.46 | - | 3.26 | - | 21.60 | - |
| 18 | | | 70 Accessory Subsystems (Start Motor, Generator, etc.) | 15.88 | 0.55 | 2.87 | 19.30 | 0.63 | 1.33 | 1.09 | 0.21 | 3.27 | - | 22.57 | - | 2,468.50 | - |
| | | | SUBSYSTEM ROLL-UP | 196.46 | 50.66 | 108.32 | 355.44 | 4.62 | 20.53 | 19.72 | 6.85 | 51.72 | - | 407.16 | - | 13,989.61 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 01 Engine System | | | | | | | | | | | | | | | | |
| 1 | | | 02 Engine Frames, Mounting, and Brackets Subsystem | 0.77 | (0.20) | (0.12) | 0.45 | 0.00 | 0.03 | 0.04 | 0.03 | 0.11 | - | 0.57 | - | (219.31) | - |
| 2 | | | 03 Crank Drive Subsystem | 6.57 | (1.05) | 1.36 | 6.88 | (0.10) | 0.27 | 0.02 | (0.02) | 0.17 | - | 7.05 | - | (480.50) | - |
| 3 | | | 04 Counter Balance Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 05 Cylinder Block Subsystem | 11.89 | 1.14 | (5.93) | 7.11 | 0.24 | 1.40 | 1.14 | 0.26 | 3.05 | - | 10.15 | - | 1,044.20 | - |
| 5 | | | 06 Cylinder Head Subsystem | 4.51 | 0.50 | 3.48 | 8.49 | 0.41 | 0.59 | 0.27 | (0.01) | 1.26 | - | 9.75 | - | 6,595.98 | - |
| 6 | | | 07 Valvetrain Subsystem | 0.68 | (0.28) | 0.03 | 0.43 | (0.01) | 0.03 | 0.04 | 0.02 | 0.07 | - | 0.50 | - | (870.40) | - |
| 7 | | | 08 Timing Drive Subsystem | (3.10) | 0.03 | 0.76 | (2.32) | 0.19 | (0.16) | (0.13) | (0.03) | (0.13) | - | (2.44) | - | 1,499.24 | - |
| 8 | | | 09 Accessory Drive Subsystem | (1.22) | 0.41 | 1.42 | 0.61 | 0.05 | 0.05 | 0.02 | 0.00 | 0.12 | - | 0.73 | - | (1,325.15) | - |
| 9 | | | 10 Air Intake Subsystem | (0.06) | (0.02) | (0.30) | (0.37) | (0.01) | (0.06) | (0.07) | (0.03) | (0.17) | - | (0.54) | - | 137.80 | - |
| 10 | | | 11 Fuel Induction Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | | | 12 Exhaust Subsystem | (12.25) | (9.46) | (5.14) | (26.85) | 1.17 | 2.91 | 2.30 | 0.47 | 6.85 | - | (20.00) | - | - | - |
| 12 | | | 13 Lubrication Subsystem | (9.53) | 0.19 | 0.53 | (8.81) | (0.28) | (0.79) | (0.66) | (0.15) | (1.88) | - | (10.69) | - | 590.10 | - |
| 13 | | | 14 Cooling Subsystem | (56.41) | (20.22) | (5.05) | (81.68) | 0.24 | (2.74) | (3.53) | (2.24) | (8.28) | - | (89.95) | - | 7,962.15 | - |
| 14 | | | 15 Induction Air Charging Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 15 | | | 16 Exhaust Gas Re-circulation Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 16 | | | 17 Breather Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 17 | | | 60 Engine Management, Engine Electronic, Electrical Subsystem | 1.65 | 0.06 | 0.04 | 1.76 | 0.00 | 0.16 | 0.07 | (0.01) | 0.22 | - | 1.97 | - | 633.60 | - |
| 18 | | | 70 Accessory Subsystems (Start Motor, Generator, etc.) | (2.50) | 0.18 | 1.32 | (1.00) | 0.00 | 0.06 | 0.04 | 0.01 | 0.11 | - | (0.89) | - | 1,402.30 | - |
| | SUBSYSTEM ROLL-UP | | | (58.99) | (28.70) | (7.59) | (95.29) | 1.92 | 1.74 | (0.46) | (1.71) | 1.49 | - | (93.80) | - | 16,964.01 | - |

### 7.1.3 Transmission System

**Table 7.1-3: Transmission System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 02 Transmission | | | | | | | | | | | | | | | | |
| 1 | | | 01 External Components | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2 | | | 02 Case Subsystem | 76.02 | 0.31 | 0.45 | 76.79 | 0.36 | 3.60 | 4.08 | 2.02 | 10.05 | - | 86.84 | - | 12,005 | - |
| 3 | | | 03 Gear Train Subsystem | 42.39 | 26.60 | 42.63 | 111.62 | 0.79 | 9.19 | 9.31 | 3.48 | 22.77 | - | 134.39 | - | 601 | - |
| 4 | | | 04 Internal Clutch Subsystem | 48.95 | 7.37 | 16.58 | 72.91 | 0.97 | 6.76 | 6.98 | 2.54 | 17.25 | - | 90.16 | - | - | - |
| 5 | | | 05 Launch Clutch Subsystem | 31.21 | 3.61 | 11.68 | 46.50 | 0.34 | 3.94 | 4.03 | 1.50 | 9.81 | - | 56.31 | - | 1,910 | - |
| 6 | | | 06 Oil Pump and Filter Subsystem | 11.89 | 2.93 | 5.37 | 20.19 | 0.14 | 1.56 | 1.63 | 0.64 | 3.97 | - | 24.16 | - | 2,018 | - |
| 7 | | | 07 Mechanical Controls Subsystem | 10.35 | - | - | 10.35 | 0.05 | 0.48 | 0.55 | 0.27 | 1.35 | - | 11.70 | - | 3,712 | - |
| 8 | | | 08 Electrical Controls Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 Parking Mechanism Subsystem | 9.08 | 0.14 | 0.56 | 9.78 | 0.10 | 0.96 | 1.10 | 0.42 | 2.57 | - | 12.35 | - | - | - |
| 10 | | | 10 Misc. Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | | | 11 Electric Motor & Controls Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 12 | | | 12 Transfer Case Subsystem | 95.51 | 24.29 | 41.96 | 161.77 | 1.24 | 13.33 | 13.64 | 5.13 | 33.34 | - | 195.11 | - | 1,591 | - |
| 13 | | | 20 Driver Operated External Controls Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 325.40 | 65.27 | 119.24 | 509.91 | 3.98 | 39.82 | 41.31 | 16.01 | 101.12 | - | 611.03 | - | 21,835 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 02 Transmission | | | | | | | | | | | | | | | | |
| 1 | | | 01 External Components | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2 | | | 02 Case Subsystem | 94.00 | 1.09 | 1.87 | 98.98 | 0.47 | 4.83 | 5.41 | 2.65 | 13.37 | - | 112.35 | - | 9,255 | - |
| 3 | | | 03 Gear Train Subsystem | 28.12 | 21.12 | 39.24 | 88.47 | 0.67 | 7.97 | 7.87 | 2.83 | 19.33 | - | 107.80 | - | 717 | - |
| 4 | | | 04 Internal Clutch Subsystem | 75.23 | 7.16 | 15.71 | 98.10 | 1.35 | 9.17 | 9.50 | 3.45 | 23.47 | - | 121.57 | - | - | - |
| 5 | | | 05 Launch Clutch Subsystem | 36.90 | 3.77 | 18.54 | 59.21 | 1.84 | 5.74 | 6.41 | 2.43 | 16.42 | - | 75.63 | - | 5,951 | - |
| 6 | | | 06 Oil Pump and Filter Subsystem | 19.93 | 2.93 | 5.37 | 28.24 | 0.20 | 2.23 | 2.32 | 0.90 | 5.65 | - | 33.89 | - | 2,636 | - |
| 7 | | | 07 Mechanical Controls Subsystem | 13.32 | - | - | 13.32 | 0.06 | 0.62 | 0.70 | 0.35 | 1.73 | - | 15.05 | - | 2,912 | - |
| 8 | | | 08 Electrical Controls Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 Parking Mechanism Subsystem | 4.69 | 0.14 | 0.56 | 5.38 | 0.05 | 0.53 | 0.60 | 0.23 | 1.41 | - | 6.80 | - | - | - |
| 10 | | | 10 Misc. Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | | | 11 Electric Motor & Controls Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 12 | | | 12 Transfer Case Subsystem | 122.91 | 24.95 | 44.08 | 191.94 | 1.53 | 17.54 | 17.36 | 6.14 | 42.57 | - | 234.51 | - | 1,461 | - |
| 13 | | | 20 Driver Operated External Controls Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 395.10 | 61.15 | 125.37 | 583.64 | 6.17 | 48.63 | 50.17 | 18.99 | 123.95 | - | 707.60 | - | 22,932 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 02 Transmission | | | | | | | | | | | | | | | | |
| 1 | | | 01 External Components | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2 | | | 02 Case Subsystem | (17.98) | (0.78) | (1.42) | (22.19) | (0.11) | (1.24) | (1.33) | (0.63) | (3.31) | - | (25.50) | - | 2,750 | - |
| 3 | | | 03 Gear Train Subsystem | 14.27 | 5.49 | 3.39 | 23.15 | 0.13 | 1.23 | 1.44 | 0.65 | 3.44 | - | 26.59 | - | (117) | - |
| 4 | | | 04 Intenal Clutch Subsystem | (20.27) | 0.21 | 0.88 | (25.19) | (0.39) | (2.42) | (2.51) | (0.91) | (6.22) | - | (31.41) | - | - | - |
| 5 | | | 05 Launch Clutch Subsystem | (5.70) | (0.16) | (6.86) | (12.71) | (1.49) | (1.80) | (2.38) | (0.93) | (6.60) | - | (19.32) | - | (4,041) | - |
| 6 | | | 06 Oil Pump and Filter Subsystem | (8.05) | - | - | (8.05) | (0.00) | (0.67) | (0.69) | (0.26) | (1.08) | - | (9.73) | - | (619) | - |
| 7 | | | 07 Mechanical Controls Subsystem | (2.90) | - | - | (2.90) | (0.01) | (0.14) | (0.16) | (0.08) | (0.39) | - | (3.35) | - | 800 | - |
| 8 | | | 08 Electrical Controls Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 Parking Mechanism Subsystem | 4.39 | - | - | 4.39 | 0.04 | 0.43 | 0.49 | 0.19 | 1.15 | - | 5.55 | - | - | - |
| 10 | | | 10 Misc. Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | | | 11 Electric Motor & Controls Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 12 | | | 12 Transfer Case Subsystem | (27.40) | (0.66) | (2.12) | (30.17) | (0.29) | (4.21) | (3.72) | (1.01) | (9.23) | - | (39.40) | - | 130 | - |
| 13 | | | 20 Driver Operated External Controls Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | SUBSYSTEM ROLL-UP | | | (69.70) | 4.11 | (6.13) | (73.73) | (2.19) | (8.81) | (8.85) | (2.98) | (22.83) | - | (96.57) | | (1,097) | |

## 7.1.4 Body System -A-

**Table 7.1-4: Body System -A- CMATs**

SYSTEM & SUBSYSTEM DESCRIPTION / BASE TECHNOLOGY GENERAL PART INFORMATION: ???

| Item | System | Subsystem | Name/Description | Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 03 Body System A | | | | | | | | | | | | | | |
| 1 | | | 01 Body Structure Subsystem | 416.93 | 21.88 | 65.64 | 504.45 | - | - | - | - | - | - | 504.45 | - | - | - |
| 2 | | | 02 Front End Subsystem | 70.07 | 4.42 | 12.78 | 87.27 | 0.11 | 1.40 | 1.29 | 0.38 | 3.18 | - | 90.45 | - | - | - |
| 3 | | | 03 Body Closure Subsystem | 339.55 | 2.42 | 7.26 | 349.23 | - | - | - | - | - | - | 349.23 | - | - | - |
| 4 | | | 19 Bumpers Subsystem | 82.07 | 1.95 | 5.84 | 89.85 | - | - | - | - | - | - | 89.85 | - | - | - |
| 5 | | | 26 Pickup Box | 240.46 | 5.63 | 16.88 | 262.96 | - | - | - | - | - | - | 262.96 | - | - | - |
| 6 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 1,149.08 | 36.29 | 108.39 | 1,293.76 | 0.11 | 1.40 | 1.29 | 0.38 | 3.18 | - | 1,296.94 | - | - | - |

SYSTEM & SUBSYSTEM DESCRIPTION / COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ???

| Item | System | Subsystem | Name/Description | Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 03 Body System A | | | | | | | | | | | | | | |
| 1 | | | 01 Body Structure Subsystem | 832.69 | 44.26 | 132.78 | 1,009.73 | - | - | - | - | - | - | 1,009.73 | - | - | - |
| 2 | | | 02 Front End Subsystem | 118.48 | 7.93 | 23.34 | 149.74 | 0.10 | 1.33 | 1.23 | 0.36 | 3.02 | - | 152.77 | - | - | - |
| 3 | | | 03 Body Closure Subsystem | 621.31 | 4.29 | 12.87 | 638.47 | - | - | - | - | - | - | 638.47 | - | - | - |
| 4 | | | 19 Bumpers Subsystem | 146.97 | 3.26 | 9.77 | 160.00 | - | - | - | - | - | - | 160.00 | - | - | - |
| 5 | | | 26 Pickup Box | 488.00 | 10.69 | 32.07 | 530.76 | - | - | - | - | - | - | 530.76 | - | - | - |
| 6 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 2,207.45 | 70.43 | 210.83 | 2,488.70 | 0.10 | 1.33 | 1.23 | 0.36 | 3.02 | - | 2,491.73 | - | - | - |

SYSTEM & SUBSYSTEM DESCRIPTION / INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE

| Item | System | Subsystem | Name/Description | Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 03 Body System A | | | | | | | | | | | | | | |
| 1 | | | 01 Body Structure Subsystem | (415.76) | (22.38) | (67.14) | (505.28) | - | - | - | - | - | - | (505.28) | - | - | - |
| 2 | | | 02 Front End Subsystem | (48.40) | (3.51) | (10.56) | (62.47) | 0.01 | 0.06 | 0.06 | 0.02 | 0.16 | - | (62.32) | - | - | - |
| 3 | | | 03 Body Closure Subsystem | (281.76) | (1.87) | (5.61) | (289.24) | - | - | - | - | - | - | (289.24) | - | - | - |
| 4 | | | 19 Bumpers Subsystem | (64.90) | (1.31) | (3.94) | (70.15) | - | - | - | - | - | - | (70.15) | - | - | - |
| 5 | | | 26 Pickup Box | (247.54) | (5.07) | (15.20) | (267.80) | - | - | - | - | - | - | (267.80) | - | - | - |
| 6 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | (1,058.36) | (34.14) | (102.44) | (1,194.94) | 0.01 | 0.06 | 0.06 | 0.02 | 0.16 | - | (1,194.79) | - | - | - |

## 7.1.5 Body System -B-

**Table 7.1-5: Body System -B- CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 03 Body Group B | | | | | | | | | | | | | | | | |
| 1 | | | 05 Interior Trim and Ornamentation Subsystem | 49.55 | 4.37 | 12.29 | 66.20 | 0.36 | 5.71 | 4.54 | 0.92 | 11.53 | - | 77.73 | - | - | - |
| 2 | | | 06 Sound and Heat Control (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 07 Sealing Subsystem | 75.49 | 27.45 | 34.31 | 137.25 | 0.75 | 11.85 | 9.41 | 1.90 | 23.91 | - | 161.16 | - | - | - |
| 4 | | | 10 Seating Subsystem | 84.10 | 13.05 | 18.86 | 116.01 | 0.38 | 6.68 | 4.90 | 1.06 | 13.02 | - | 129.02 | - | 10,540 | - |
| 5 | | | 12 Instrument Panel and Console Subsystem | 55.06 | 5.51 | 10.21 | 70.77 | 0.29 | 4.85 | 3.71 | 0.78 | 9.63 | - | 80.40 | - | 4,054 | - |
| 6 | | | 20 Occupant Restraining Devices | 14.04 | 4.42 | 5.24 | 23.69 | 0.12 | 1.40 | 1.40 | 0.58 | 3.50 | - | 27.20 | - | 2,365 | - |
| 7 | | | 27 Cockpit Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 29 Overhead Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 30 Carpet Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 31 Package Tray Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | | | 34 Floor and Tunnel Console Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 278.23 | 54.79 | 80.90 | 413.92 | 1.91 | 30.50 | 23.95 | 5.23 | 61.58 | - | 475.51 | - | 16,958 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 03 Body Group B | | | | | | | | | | | | | | | | |
| 1 | | | 05 Interior Trim and Ornamentation Subsystem | 46.82 | 3.86 | 9.70 | 60.38 | 0.33 | 5.21 | 4.14 | 0.84 | 10.52 | - | 70.90 | - | - | - |
| 2 | | | 06 Sound and Heat Control (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 07 Sealing Subsystem | 71.37 | 16.47 | 21.96 | 109.80 | 0.60 | 9.48 | 7.53 | 1.52 | 19.12 | - | 128.92 | - | - | - |
| 4 | | | 10 Seating Subsystem | 172.42 | 17.84 | 45.32 | 235.58 | 0.60 | 11.09 | 7.81 | 1.83 | 21.33 | - | 256.91 | - | 16,699 | - |
| 5 | | | 12 Instrument Panel and Console Subsystem | 75.72 | 8.69 | 19.51 | 103.92 | 0.35 | 6.00 | 4.45 | 0.98 | 11.77 | - | 115.69 | - | 2,599 | - |
| 6 | | | 20 Occupant Restraining Devices | 14.72 | 3.85 | 7.91 | 26.48 | 0.13 | 1.52 | 1.54 | 0.65 | 3.84 | - | 30.32 | - | 365 | - |
| 7 | | | 27 Cockpit Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 29 Overhead Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 30 Carpet Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 31 Package Tray Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | | | 34 Floor and Tunnel Console Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 381.05 | 50.71 | 104.40 | 536.16 | 2.01 | 33.30 | 25.47 | 5.81 | 66.58 | - | 602.74 | - | 19,663.00 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 03 Body Group B | | | | | | | | | | | | | | | | |
| 1 | | | 05 Interior Trim and Ornamentation Subsystem | 2.72 | 0.51 | 2.59 | 5.82 | 0.03 | 0.50 | 0.40 | 0.08 | 1.01 | - | 6.84 | - | - | - |
| 2 | | | 06 Sound and Heat Control (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 07 Sealing Subsystem | 4.12 | 10.98 | 12.35 | 27.45 | 0.15 | 2.37 | 1.88 | 0.38 | 4.78 | - | 32.23 | - | - | - |
| 4 | | | 10 Seating Subsystem | (88.32) | (4.80) | (26.46) | (119.58) | (0.22) | (4.41) | (2.91) | (0.77) | (8.31) | - | (127.89) | - | (6,159) | - |
| 5 | | | 12 Instrument Panel and Console Subsystem | (20.66) | (3.18) | (9.30) | (33.15) | (0.06) | (1.14) | (0.75) | (0.20) | (2.15) | - | (35.29) | - | 1,455 | - |
| 6 | | | 20 Occupant Restraining Devices | (0.68) | 0.57 | (2.67) | (2.78) | (0.01) | (0.12) | (0.14) | (0.07) | (0.34) | - | (3.12) | - | 2,000 | - |
| 7 | | | 27 Cockpit Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 29 Overhead Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 30 Carpet Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 31 Package Tray Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | | | 34 Floor and Tunnel Console Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | (102.81) | 4.06 | (23.50) | (122.23) | (0.10) | (2.80) | (1.51) | (0.58) | (5.00) | - | (127.23) | - | (2,705) | - |

## 7.1.6 Body System -C-

**Table 7.1-6: Body System -C- CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 03 Body System C | | | | | | | | | | | | | | |
| 1 | | | 08 Exterior Trim & Ornamentation | 22.44 | 0.71 | 1.40 | 24.54 | 0.13 | 2.12 | 1.68 | 0.34 | 4.27 | - | 28.81 | - | - | - |
| 2 | | | 09 Rear View Mirrors | 9.50 | 0.55 | 0.93 | 10.98 | 0.06 | 0.95 | 0.75 | 0.15 | 1.91 | - | 12.90 | - | - | - |
| 3 | | | 23 Front End Modules | 13.05 | 0.46 | 0.97 | 14.48 | 0.08 | 1.25 | 0.99 | 0.20 | 2.52 | - | 17.00 | - | - | - |
| 4 | | | 24 Rear End Modules | 4.55 | 0.17 | 0.29 | 5.01 | 0.03 | 0.43 | 0.34 | 0.07 | 0.87 | - | 5.88 | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 49.53 | 1.89 | 3.59 | 55.02 | 0.30 | 4.75 | 3.77 | 0.76 | 9.58 | - | 64.60 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 03 Body System C | | | | | | | | | | | | | | |
| 1 | | | 08 Exterior Trim & Ornamentation | 21.79 | 0.63 | 1.23 | 23.64 | 0.13 | 2.04 | 1.62 | 0.33 | 4.12 | - | 27.76 | - | - | - |
| 2 | | | 09 Rear View Mirrors | 8.91 | 0.47 | 0.80 | 10.18 | 0.06 | 0.88 | 0.70 | 0.14 | 1.77 | - | 11.96 | - | - | - |
| 3 | | | 23 Front End Modules | 12.78 | 0.41 | 0.86 | 14.05 | 0.08 | 1.21 | 0.96 | 0.19 | 2.45 | - | 16.50 | - | - | - |
| 4 | | | 24 Rear End Modules | 4.41 | 0.14 | 0.25 | 4.81 | 0.03 | 0.41 | 0.33 | 0.07 | 0.84 | - | 5.64 | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 47.89 | 1.65 | 3.15 | 52.69 | 0.29 | 4.55 | 3.61 | 0.73 | 9.18 | - | 61.86 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 03 Body System C | | | | | | | | | | | | | | |
| 1 | | | 08 Exterior Trim & Ornamentation | 0.65 | 0.08 | 0.16 | 0.90 | 0.00 | 0.08 | 0.06 | 0.01 | 0.16 | - | 1.05 | - | - | - |
| 2 | | | 09 Rear View Mirrors | 0.59 | 0.08 | 0.13 | 0.80 | 0.00 | 0.07 | 0.05 | 0.01 | 0.14 | - | 0.94 | - | - | - |
| 3 | | | 23 Front End Modules | 0.26 | 0.05 | 0.11 | 0.43 | 0.00 | 0.04 | 0.03 | 0.01 | 0.07 | - | 0.50 | - | - | - |
| 4 | | | 24 Rear End Modules | 0.13 | 0.03 | 0.05 | 0.20 | 0.00 | 0.02 | 0.01 | 0.00 | 0.04 | - | 0.24 | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 1.64 | 0.24 | 0.45 | 2.33 | 0.01 | 0.20 | 0.16 | 0.03 | 0.41 | - | 2.73 | - | - | - |

### 7.1.7 Body System -D-

**Table 7.1-7: Body System -D- CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 03 Body System D | | | | | | | | | | | | | | |
| 1 | | | 11 Glass (Glazing), Frame and Mechanisms | 13.91 | 3.24 | 81.74 | 98.89 | 0.46 | 4.58 | 5.23 | 2.62 | 12.88 | - | 111.77 | - | - | - |
| 2 | | | 14 Handles, Locks, Latches, and Mechanisms | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 15 Rear Hatch Lift (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 16 Wipers and Washers | 1.51 | 0.07 | 0.12 | 1.70 | 0.01 | 0.16 | 0.17 | 0.06 | 0.40 | - | 2.10 | - | - | - |
| 5 | | | 25 Liftgate Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 28 Wiper and Cowl Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 33 Door Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 15.43 | 3.31 | 81.85 | 100.59 | 0.47 | 4.74 | 5.40 | 2.68 | 13.28 | - | 113.87 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 03 Body System D | | | | | | | | | | | | | | |
| 1 | | | 11 Glass (Glazing), Frame and Mechanisms | 11.94 | 4.15 | 81.74 | 97.82 | 0.45 | 4.49 | 5.13 | 2.56 | 12.62 | - | 109.54 | - | - | - |
| 2 | | | 14 Handles, Locks, Latches, and Mechanisms | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 15 Rear Hatch Lift (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 16 Wipers and Washers | 1.48 | 0.06 | 0.11 | 1.65 | 0.01 | 0.15 | 0.16 | 0.06 | 0.39 | - | 2.03 | - | - | - |
| 5 | | | 25 Liftgate Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 28 Wiper and Cowl Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 33 Door Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 13.42 | 4.21 | 81.84 | 99.47 | 0.46 | 4.64 | 5.29 | 2.62 | 13.01 | - | 111.57 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 03 Body System D | | | | | | | | | | | | | | |
| 1 | | | 11 Glass (Glazing), Frame and Mechanisms | 1.98 | (0.91) | - | 1.07 | 0.01 | 0.09 | 0.10 | 0.05 | 0.26 | - | 2.23 | - | - | - |
| 2 | | | 14 Handles, Locks, Latches, and Mechanisms | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 15 Rear Hatch Lift (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 16 Wipers and Washers | 0.03 | 0.01 | 0.01 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | - | 0.06 | - | - | - |
| 5 | | | 25 Liftgate Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 28 Wiper and Cowl Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 33 Door Modules (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 2.01 | (0.90) | 0.01 | 1.12 | 0.01 | 0.10 | 0.11 | 0.05 | 0.27 | - | 2.30 | - | - | - |

## 7.1.8 Suspension System

**Table 7.1-8: Suspension System CMATs**

| Item | System | Subsystem | Name/Description (SYSTEM & SUBSYSTEM DESCRIPTION) | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? — Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | **04 Suspension System** | | | | | | | | | | | | | | |
| 1 | | | 01 Front Suspension Subsystem | 58.49 | 8.60 | 44.71 | 111.80 | 0.61 | 6.57 | 7.06 | 3.14 | 17.38 | - | 129.19 | - | 5,240.30 | - |
| 2 | | | 02 Rear Suspension Subsystem | 121.36 | 12.35 | 49.36 | 183.07 | 1.11 | 9.53 | 10.43 | 4.89 | 25.96 | - | 209.03 | - | 1,932.70 | - |
| 3 | | | 03 Shock Absorber Subsystem | 27.38 | 3.23 | 13.96 | 44.57 | 0.23 | 2.45 | 2.63 | 1.19 | 6.50 | - | 51.07 | - | 483.02 | - |
| 4 | | | 04 Wheels and Tires Subsystem | 400.94 | 59.54 | 134.93 | 595.41 | 2.76 | 27.69 | 31.58 | 15.75 | 77.79 | - | 673.20 | - | 942.90 | - |
| 5 | | | 05 Suspension Load Leveling Control Subsystem (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 Rear suspension Modules Subsystem (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 Front Suspension Modules Subsystem (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 608.17 | 83.72 | 242.96 | 934.85 | 4.71 | 46.24 | 51.70 | 24.98 | 127.63 | - | 1,062.49 | - | 8,598.92 | - |

| Item | System | Subsystem | Name/Description (SYSTEM & SUBSYSTEM DESCRIPTION) | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? — Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | **04 Suspension System** | | | | | | | | | | | | | | |
| 1 | | | 01 Front Suspension Subsystem | 65.34 | 9.54 | 50.26 | 125.13 | 0.62 | 6.54 | 7.14 | 3.39 | 17.69 | - | 142.82 | - | 6,457.48 | - |
| 2 | | | 02 Rear Suspension Subsystem | 172.43 | 24.12 | 60.78 | 257.33 | 1.66 | 12.92 | 14.33 | 6.86 | 35.76 | - | 293.09 | - | 2,019.46 | - |
| 3 | | | 03 Shock Absorber Subsystem | 21.37 | 3.70 | 20.09 | 45.16 | 0.24 | 2.60 | 2.75 | 1.22 | 6.80 | - | 51.96 | - | 570.62 | - |
| 4 | | | 04 Wheels and Tires Subsystem | 419.57 | 64.52 | 161.11 | 645.19 | 2.99 | 30.02 | 34.24 | 17.07 | 84.33 | - | 729.52 | - | 922.90 | - |
| 5 | | | 05 Suspension Load Leveling Control Subsystem (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 Rear suspension Modules Subsystem (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 Front Suspension Modules Subsystem (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 678.70 | 101.88 | 292.23 | 1,072.82 | 5.51 | 52.08 | 58.46 | 28.53 | 144.57 | - | 1,217.39 | - | 9,970.45 | - |

| Item | System | Subsystem | Name/Description (SYSTEM & SUBSYSTEM DESCRIPTION) | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE — Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | **04 Suspension System** | | | | | | | | | | | | | | |
| 1 | | | 01 Front Suspension Subsystem | (6.85) | (0.94) | (5.54) | (13.33) | (0.01) | 0.03 | (0.08) | (0.24) | (0.30) | - | (13.64) | - | (1,217.18) | - |
| 2 | | | 02 Rear Suspension Subsystem | (51.07) | (11.77) | (11.42) | (74.26) | (0.55) | (3.39) | (3.90) | (1.97) | (9.79) | - | (84.06) | - | (86.75) | - |
| 3 | | | 03 Shock Absorber Subsystem | 6.01 | (0.47) | (6.13) | (0.58) | (0.01) | (0.15) | (0.12) | (0.02) | (0.30) | - | (0.89) | - | (87.60) | - |
| 4 | | | 04 Wheels and Tires Subsystem | (18.63) | (4.98) | (26.18) | (49.78) | (0.23) | (2.33) | (2.65) | (1.32) | (6.54) | - | (56.32) | - | 20.00 | - |
| 5 | | | 05 Suspension Load Leveling Control Subsystem (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 Rear suspension Modules Subsystem (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 Front Suspension Modules Subsystem (NA) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | (70.53) | (18.16) | (49.27) | (137.96) | (0.80) | (5.84) | (6.75) | (3.55) | (16.94) | - | (154.90) | - | (1,371.54) | - |

## 7.1.9 Driveline System

**Table 7.1-9: Driveline System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 05 Driveline | | | | | | | | | | | | | | |
| 1 | | | 01 Driveshaft Subsystem | 4.86 | 3.03 | 9.91 | 17.81 | 0.12 | 1.60 | 1.48 | 0.45 | 3.66 | - | 21.46 | - | - | - |
| 2 | | | 02 Rear Drive Housed Axle Subsystem | 103.09 | 13.80 | 49.23 | 166.12 | 1.72 | 15.06 | 14.22 | 4.50 | 35.50 | - | 201.63 | - | 710.00 | - |
| 3 | | | 03 Front Drive Housed Axle Subsystem | 47.75 | 11.61 | 35.81 | 95.17 | 1.20 | 8.70 | 8.36 | 2.75 | 21.00 | - | 116.18 | - | 721.25 | - |
| 4 | | | 04 Front Drive Half-Shafts Subsystem | 12.99 | 3.92 | 9.50 | 26.41 | 0.08 | 1.12 | 0.99 | 0.15 | 2.34 | - | 28.76 | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 168.70 | 32.36 | 104.45 | 305.52 | 3.13 | 26.48 | 25.05 | 7.85 | 62.51 | - | 368.03 | - | 1,431.25 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 05 Driveline | | | | | | | | | | | | | | |
| 1 | | | 01 Driveshaft Subsystem | 3.26 | 2.76 | 9.02 | 15.04 | 0.10 | 1.35 | 1.22 | 0.37 | 3.04 | - | 18.08 | - | - | - |
| 2 | | | 02 Rear Drive Housed Axle Subsystem | 79.07 | 15.69 | 50.68 | 145.44 | 1.03 | 13.14 | 12.35 | 3.89 | 30.41 | - | 175.85 | - | 274.80 | - |
| 3 | | | 03 Front Drive Housed Axle Subsystem | 33.18 | 15.06 | 42.62 | 90.87 | 0.65 | 8.15 | 7.72 | 2.55 | 19.06 | - | 109.91 | - | 134.30 | - |
| 4 | | | 04 Front Drive Half-Shafts Subsystem | 10.85 | 5.19 | 7.90 | 23.94 | 0.07 | 1.01 | 0.89 | 0.26 | 2.24 | - | 26.18 | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 126.36 | 38.71 | 110.22 | 275.28 | 1.86 | 23.65 | 22.17 | 7.07 | 54.74 | - | 330.01 | - | 409.10 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 05 Driveline | | | | | | | | | | | | | | |
| 1 | | | 01 Driveshaft Subsystem | 1.60 | 0.27 | 0.89 | 2.76 | 0.02 | 0.26 | 0.26 | 0.08 | 0.62 | - | 3.38 | - | - | - |
| 2 | | | 02 Rear Drive Housed Axle Subsystem | 24.02 | (1.88) | (1.45) | 20.69 | 0.69 | 1.92 | 1.87 | 0.61 | 5.09 | - | 25.78 | - | 435.20 | - |
| 3 | | | 03 Front Drive Housed Axle Subsystem | 14.57 | (3.45) | (6.81) | 4.31 | 0.55 | 0.55 | 0.64 | 0.20 | 1.95 | - | 6.27 | - | 586.95 | - |
| 4 | | | 04 Front Drive Half-Shafts Subsystem | 2.14 | (1.28) | 1.61 | 2.47 | 0.01 | 0.11 | 0.11 | (0.12) | 0.11 | - | 2.58 | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 42.34 | (6.34) | (5.76) | 30.23 | 1.27 | 2.84 | 2.88 | 0.78 | 7.77 | - | 38.01 | - | 1,022.15 | - |

### 7.1.10 Brakes System

**Table 7.1-10: Brakes System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | System | Subsystem | Name/Description | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | **06 Brake System** | | | | | | | | | | | | | | |
| 1 | | | 01 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2 | | | 02 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Front Rotor/Drum and Shield Subsystem | 54.61 | 8.36 | 40.49 | 103.46 | 0.52 | 5.39 | 6.00 | 2.93 | 14.84 | - | 118.30 | - | 3,509.50 | - |
| 4 | | | 04 Rear Rotor/Drum and Shield Subsystem | 40.54 | 4.75 | 29.87 | 75.16 | 0.39 | 4.20 | 4.54 | 2.11 | 11.24 | - | 86.40 | - | 2,125.10 | - |
| 5 | | | 05 Parking Brake and Actuation Subsystem | 18.54 | 5.16 | 8.88 | 32.59 | 0.17 | 2.60 | 2.13 | 0.72 | 5.62 | - | 38.21 | - | 654.84 | - |
| 6 | | | 06 Brake Actuation Subsystem | 12.64 | 1.83 | 3.77 | 18.24 | 0.13 | 1.64 | 1.58 | 0.55 | 3.90 | - | 22.14 | - | 1,405.07 | - |
| 7 | | | 07 Power Brake Subsystem (for Hydraulic) | 6.52 | 1.13 | 2.59 | 10.24 | 0.07 | 0.92 | 0.86 | 0.29 | 2.14 | - | 12.38 | - | 2,651.35 | - |
| 8 | | | 08 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 Brake Controls Subsystem (N/A) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 Auxiliary Brake Subsystem (N/A) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 132.86 | 21.22 | 85.60 | 239.68 | 1.29 | 14.75 | 15.11 | 6.60 | 37.75 | - | 277.43 | - | 10,345.86 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | System | Subsystem | Name/Description | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | **06 Brake System** | | | | | | | | | | | | | | |
| 1 | | | 01 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2 | | | 02 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Front Rotor/Drum and Shield Subsystem | 105.45 | 8.20 | 29.95 | 143.60 | 0.71 | 7.21 | 8.13 | 4.01 | 20.05 | - | 163.65 | - | 5,922.08 | - |
| 4 | | | 04 Rear Rotor/Drum and Shield Subsystem | 94.56 | 5.57 | 28.69 | 128.82 | 1.33 | 7.33 | 8.10 | 3.73 | 20.49 | - | 149.31 | - | 3,315.95 | - |
| 5 | | | 05 Parking Brake and Actuation Subsystem | 20.97 | 7.40 | 18.82 | 47.19 | 0.36 | 4.14 | 4.23 | 1.87 | 10.60 | - | 57.79 | - | 2,598.04 | - |
| 6 | | | 06 Brake Actuation Subsystem | 11.90 | 1.48 | 4.98 | 18.36 | 0.15 | 1.71 | 1.75 | 0.63 | 4.24 | - | 22.60 | - | 3,298.65 | - |
| 7 | | | 07 Power Brake Subsystem (for Hydraulic) | 8.20 | 3.45 | 17.26 | 28.90 | 0.98 | 2.82 | 3.14 | 1.19 | 8.12 | - | 37.02 | - | 4,192.32 | - |
| 8 | | | 08 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 Brake Controls Subsystem (N/A) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 Auxiliary Brake Subsystem (N/A) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 241.08 | 26.10 | 99.69 | 366.87 | 3.51 | 23.21 | 25.36 | 11.43 | 63.50 | - | 430.37 | - | 19,327.04 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | System | Subsystem | Name/Description | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | **06 Brake System** | | | | | | | | | | | | | | |
| 1 | | | 01 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 2 | | | 02 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Front Rotor/Drum and Shield Subsystem | (50.84) | 0.16 | 10.54 | (40.14) | (0.19) | (1.82) | (2.13) | (1.08) | (5.21) | - | (45.35) | - | (2,412.58) | - |
| 4 | | | 04 Rear Rotor/Drum and Shield Subsystem | (54.02) | (0.83) | 1.18 | (53.66) | (0.94) | (3.13) | (3.56) | (1.62) | (9.25) | - | (62.91) | - | (1,190.85) | - |
| 5 | | | 05 Parking Brake and Actuation Subsystem | (2.43) | (2.23) | (9.94) | (14.60) | (0.18) | (1.54) | (2.10) | (1.15) | (4.98) | - | (19.58) | - | (1,943.20) | - |
| 6 | | | 06 Brake Actuation Subsystem | 0.74 | 0.35 | (1.20) | (0.12) | (0.02) | (0.06) | (0.17) | (0.08) | (0.34) | - | (0.46) | - | (1,893.58) | - |
| 7 | | | 07 Power Brake Subsystem (for Hydraulic) | (1.68) | (2.32) | (14.67) | (18.66) | (0.89) | (1.91) | (2.28) | (0.90) | (5.97) | - | (24.64) | - | (1,540.97) | - |
| 8 | | | 08 N / A | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 Brake Controls Subsystem (N/A) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 Auxiliary Brake Subsystem (N/A) | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | (108.23) | (4.87) | (14.09) | (127.19) | (2.22) | (8.45) | (10.25) | (4.83) | (25.75) | - | (152.94) | - | (8,981.18) | - |

### 7.1.11 Frame and Mounting System

**Table 7.1-11: Frame and Mounting System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 07 Frame and Mounting System | | | | | | | | | | | | | | |
| 1 | | | 01 Frame Sub System | 479.02 | - | - | 479.02 | - | - | - | - | - | - | 479.02 | - | - | - |
| 2 | | | 02 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 479.02 | - | - | 479.02 | - | - | - | - | - | - | 479.02 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 07 Frame and Mounting System | | | | | | | | | | | | | | |
| 1 | | | 01 Frame Sub System | 533.44 | - | - | 533.44 | - | - | - | - | - | - | 533.44 | - | - | - |
| 2 | | | 02 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 533.44 | - | - | 533.44 | - | - | - | - | - | - | 533.44 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 07 Frame and Mounting System | | | | | | | | | | | | | | |
| 1 | | | 01 Frame Sub System | (54.42) | - | - | (54.42) | - | - | - | - | - | - | (54.42) | - | - | - |
| 2 | | | 02 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | (54.42) | - | - | (54.42) | - | - | - | - | - | - | (54.42) | - | - | - |

### 7.1.12 Exhaust System

**Table 7.1-12: Exhaust System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 09 Exhaust System | | | | | | | | | | | | | | |
| 1 | | | 01 Acoustical Control Components | 31.13 | 1.67 | 4.32 | 37.12 | 0.24 | 3.24 | 2.91 | 0.85 | 7.24 | - | 44.35 | - | - | - |
| 2 | | | 02 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 31.13 | 1.67 | 4.32 | 37.12 | 0.24 | 3.24 | 2.91 | 0.85 | 7.24 | - | 44.35 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 09 Exhaust System | | | | | | | | | | | | | | |
| 1 | | | 01 Acoustical Control Components | 44.45 | 0.61 | 3.26 | 48.31 | 0.32 | 4.43 | 3.89 | 1.09 | 9.73 | - | 58.04 | - | - | - |
| 2 | | | 02 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 44.45 | 0.61 | 3.26 | 48.31 | 0.32 | 4.43 | 3.89 | 1.09 | 9.73 | - | 58.04 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | Total Manufacturing Cost (Component/ Assembly) | Markup | | | | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | | End Item Scrap | SG&A | Profit | ED&T-R&D | | | | | | |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 09 Exhaust System | | | | | | | | | | | | | | |
| 1 | | | 01 Acoustical Control Components | (13.32) | 1.06 | 1.06 | (11.19) | (0.08) | (1.19) | (0.98) | (0.24) | (2.49) | - | (13.69) | - | - | - |
| 2 | | | 02 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | (13.32) | 1.06 | 1.06 | (11.19) | (0.08) | (1.19) | (0.98) | (0.24) | (2.49) | - | (13.69) | - | - | - |

## 7.1.13 Fuel System

**Table 7.1-13: Fuel System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 10 Fuel System | | | | | | | | | | | | | | |
| 1 | | | 01 Fuel Tank and Lines Subsystem | 124.87 | 1.38 | 17.21 | 143.47 | 0.50 | 6.77 | 6.03 | 2.29 | 15.60 | - | 159.06 | - | 2,501 | - |
| 2 | | | 02 Fuel Vapor Management Subsystem | 6.20 | 1.75 | 1.94 | 9.90 | 0.04 | 0.81 | 0.55 | 0.07 | 1.47 | - | 11.37 | - | 503 | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 131.07 | 3.13 | 19.16 | 153.36 | 0.54 | 7.58 | 6.58 | 2.37 | 17.07 | - | 170.43 | - | 3,004 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 10 Fuel System | | | | | | | | | | | | | | |
| 1 | | | 01 Fuel Tank and Lines Subsystem | 116.27 | 1.21 | 16.00 | 133.48 | 0.47 | 6.27 | 5.65 | 2.17 | 14.56 | - | 148.03 | - | 734 | - |
| 2 | | | 02 Fuel Vapor Management Subsystem | 5.24 | 1.70 | 2.15 | 9.09 | 0.04 | 0.75 | 0.52 | 0.08 | 1.39 | - | 10.48 | - | 272 | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 121.50 | 2.91 | 18.15 | 142.57 | 0.51 | 7.02 | 6.17 | 2.25 | 15.94 | - | 158.51 | - | 1,006 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 10 Fuel System | | | | | | | | | | | | | | |
| 1 | | | 01 Fuel Tank and Lines Subsystem | 8.61 | 0.17 | 1.21 | 9.99 | 0.03 | 0.50 | 0.39 | 0.13 | 1.04 | - | 11.03 | - | 1,767 | - |
| 2 | | | 02 Fuel Vapor Management Subsystem | 0.96 | 0.04 | (0.20) | 0.81 | 0.00 | 0.06 | 0.03 | (0.00) | 0.09 | - | 0.89 | - | 231 | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 9.57 | 0.22 | 1.01 | 10.80 | 0.03 | 0.56 | 0.41 | 0.12 | 1.12 | - | 11.92 | - | 1,999 | - |

## 7.1.14 Steering System

**Table 7.1-14: Steering System CMATs**

**SYSTEM & SUBSYSTEM DESCRIPTION / BASE TECHNOLOGY GENERAL PART INFORMATION: ???**

| Item | System | Subsystem | Name/Description | Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 11 | | **Steering System** | | | | | | | | | | | | | | |
| 1 | | | 01 Steering Gear Sub-System | 65.57 | 24.81 | 30.33 | 120.71 | 1.30 | 11.85 | 13.32 | 7.75 | 34.22 | - | 154.94 | - | - | - |
| 2 | | | 02 Power Steering Pump | 36.00 | - | - | 36.00 | 0.17 | 1.67 | 1.90 | 0.95 | 4.69 | - | 40.69 | - | - | - |
| 3 | | | 03 Power Steering Equipmen | 25.22 | 8.41 | 8.41 | 42.03 | 0.42 | 4.17 | 4.77 | 2.94 | 12.29 | - | 54.32 | - | - | - |
| 4 | | | 04 Steering Column Assembly | 24.45 | 5.28 | 8.80 | 38.53 | 0.44 | 3.03 | 3.13 | 1.24 | 7.84 | - | 46.37 | - | 2,366.50 | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 151.24 | 38.50 | 47.54 | 237.27 | 2.32 | 20.72 | 23.12 | 12.88 | 59.04 | - | 296.32 | - | 2,366.50 | - |

**SYSTEM & SUBSYSTEM DESCRIPTION / COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ???**

| Item | System | Subsystem | Name/Description | Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 11 | | **Steering System** | | | | | | | | | | | | | | |
| 1 | | | 01 Steering Gear Sub-System | 181.80 | 63.79 | 66.38 | 311.97 | 3.06 | 30.84 | 35.05 | 21.25 | 90.20 | - | 402.17 | - | - | - |
| 2 | | | 02 Power Steering Pump | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Power Steering Equipmen | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 Steering Column Assembly | 19.70 | 3.50 | 11.15 | 34.35 | 0.58 | 2.73 | 2.84 | 1.11 | 7.26 | - | 41.61 | - | 2,620.50 | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 201.50 | 67.30 | 77.53 | 346.32 | 3.64 | 33.56 | 37.90 | 22.37 | 97.46 | - | 443.78 | - | 2,620.50 | - |

**SYSTEM & SUBSYSTEM DESCRIPTION / INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE**

| Item | System | Subsystem | Name/Description | Manufacturing: Material | Manufacturing: Labor | Manufacturing: Burden | Total Manufacturing Cost (Component/ Assembly) | Markup: End Item Scrap | Markup: SG&A | Markup: Profit | Markup: ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 11 | | **Steering System** | | | | | | | | | | | | | | |
| 1 | | | 01 Steering Gear Sub-System | (116.23) | (38.98) | (36.05) | (191.26) | (1.76) | (18.99) | (21.73) | (13.50) | (55.98) | - | (247.24) | - | - | - |
| 2 | | | 02 Power Steering Pump | 36.00 | - | - | 36.00 | 0.17 | 1.67 | 1.90 | 0.95 | 4.69 | - | 40.69 | - | - | - |
| 3 | | | 03 Power Steering Equipmen | 25.22 | 8.41 | 8.41 | 42.03 | 0.42 | 4.17 | 4.77 | 2.94 | 12.29 | - | 54.32 | - | - | - |
| 4 | | | 04 Steering Column Assembly | 4.75 | 1.78 | (2.35) | 4.18 | (0.14) | 0.30 | 0.29 | 0.12 | 0.58 | - | 4.76 | - | (254.00) | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | (50.25) | (28.80) | (29.99) | (109.05) | (1.32) | (12.85) | (14.77) | (9.49) | (38.42) | - | (147.46) | - | (254.00) | - |

### 7.1.15 Climate Control System

**Table 7.1-15: Climate Control System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 12 Climate Control | | | | | | | | | | | | | | | | |
| 1 | | | 01 Air Handling / Body Ventilation Subsystem | 17.91 | 3.84 | 20.23 | 41.98 | 0.32 | 3.86 | 3.83 | 1.30 | 9.31 | - | 51.29 | - | - | - |
| 2 | | | 02 Heating / Defrosting Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Refrigeration / Air Conditioning Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 Controls Subsytem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 17.91 | 3.84 | 20.23 | 41.98 | 0.32 | 3.86 | 3.83 | 1.30 | 9.31 | - | 51.29 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 12 Climate Control | | | | | | | | | | | | | | | | |
| 1 | | | 01 Air Handling / Body Ventilation Subsystem | 14.41 | 4.32 | 10.93 | 29.67 | 0.25 | 2.77 | 2.86 | 1.04 | 6.91 | - | 36.58 | - | - | - |
| 2 | | | 02 Heating / Defrosting Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Refrigeration / Air Conditioning Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 Controls Subsytem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 14.41 | 4.32 | 10.93 | 29.67 | 0.25 | 2.77 | 2.86 | 1.04 | 6.91 | - | 36.58 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 12 Climate Control | | | | | | | | | | | | | | | | |
| 1 | | | 01 Air Handling / Body Ventilation Subsystem | 3.50 | (0.49) | 9.30 | 12.31 | 0.08 | 1.09 | 0.96 | 0.26 | 2.40 | - | 14.71 | - | - | - |
| 2 | | | 02 Heating / Defrosting Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Refrigeration / Air Conditioning Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 Controls Subsytem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 3.50 | (0.49) | 9.30 | 12.31 | 0.08 | 1.09 | 0.96 | 0.26 | 2.40 | - | 14.71 | - | - | - |

## 7.1.16 Info, Gage, and Warning System

**Table 7.1-16: Info, Gage, and Warning System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 12 Climate Control | | | | | | | | | | | | | | |
| 1 | | | 01 Air Handling / Body Ventilation Subsystem | 3.50 | (0.49) | 9.30 | 12.31 | 0.08 | 1.09 | 0.96 | 0.26 | 2.40 | - | 14.71 | - | - | - |
| 2 | | | 02 Heating / Defrosting Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Refrigeration / Air Conditioning Subsystem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 Controls Subsytem | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 3.50 | (0.49) | 9.30 | 12.31 | 0.08 | 1.09 | 0.96 | 0.26 | 2.40 | - | 14.71 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 13 Info,Gage and Warning system Total | | | | | | | | | | | | | | |
| 1 | | | 01Driver Information Module (Instrument Cluster) | 1.51 | 0.32 | 0.86 | 2.69 | 0.01 | 0.23 | 0.18 | 0.04 | 0.47 | - | 3.15 | - | - | - |
| 2 | | | 02 Traffic Horns (Electric) | 1.04 | 0.21 | 0.57 | 1.83 | 0.01 | 0.16 | 0.13 | 0.03 | 0.32 | - | 2.14 | - | 376.10 | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 2.54 | 0.53 | 1.43 | 4.51 | 0.02 | 0.39 | 0.31 | 0.06 | 0.79 | - | 5.30 | - | 376.10 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | | | 13 Info,Gage and Warning system Total | | | | | | | | | | | | | | |
| 1 | | | 01Driver Information Module (Instrument Cluster) | 0.06 | 0.05 | 0.31 | 0.41 | 0.00 | 0.04 | 0.03 | 0.01 | 0.07 | - | 0.49 | - | - | - |
| 2 | | | 02 Traffic Horns (Electric) | 0.17 | (0.04) | 0.02 | 0.16 | 0.00 | 0.01 | 0.00 | (0.00) | 0.01 | - | 0.17 | - | 143.80 | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 0.23 | 0.01 | 0.34 | 0.57 | 0.00 | 0.05 | 0.03 | 0.00 | 0.09 | - | 0.66 | - | 143.80 | - |

## 7.1.17 Electrical Power Supply System

**Table 7.1-17: Electrical Power Supply System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 14 | | Electrical Power Supply | | | | | | | | | | | | | | |
| 1 | | 01 | Service Battery Subsystem | 23.21 | 6.51 | 6.51 | 36.23 | 0.10 | 1.66 | 1.23 | 0.35 | 3.33 | - | 39.56 | - | 1,429.57 | - |
| 2 | | 02 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | 03 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | 04 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | 05 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | 06 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | 07 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | 08 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | 09 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | 10 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 23.21 | 6.51 | 6.51 | 36.23 | 0.10 | 1.66 | 1.23 | 0.35 | 3.33 | - | 39.56 | - | 1,429.57 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 14 | | Electrical Power Supply | | | | | | | | | | | | | | |
| 1 | | 01 | Service Battery Subsystem | 119.32 | 37.92 | 39.03 | 196.27 | 0.44 | 8.24 | 5.79 | 1.55 | 16.02 | - | 212.29 | - | 243.62 | - |
| 2 | | 02 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | 03 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | 04 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | 05 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | 06 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | 07 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | 08 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | 09 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | 10 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 119.32 | 37.92 | 39.03 | 196.27 | 0.44 | 8.24 | 5.79 | 1.55 | 16.02 | - | 212.29 | - | 243.62 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 14 | | Electrical Power Supply | | | | | | | | | | | | | | |
| 1 | | 01 | Service Battery Subsystem | (96.12) | (31.40) | (32.51) | (160.04) | (0.35) | (6.57) | (4.57) | (1.20) | (12.69) | - | (172.73) | - | 1,185.96 | - |
| 2 | | 02 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | 03 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | 04 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | 05 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | 06 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | 07 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | 08 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | 09 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | 10 | | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | (96.12) | (31.40) | (32.51) | (160.04) | (0.35) | (6.57) | (4.57) | (1.20) | (12.69) | - | (172.73) | - | 1,185.96 | - |

### 7.1.18 Lighting System

**Table 7.1-18: Lighting System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 17 Lighting System | | | | | | | | | | | | | | | | |
| 1 | | | 01 Front Lighting | 6.36 | 1.15 | 2.80 | 10.31 | 0.05 | 0.48 | 0.55 | 0.27 | 1.34 | - | 11.65 | - | - | - |
| 2 | | | 02 Interior Lighting | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Rear Lighting | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 Special Mechanisms | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 Lighting Switches | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 6.36 | 1.15 | 2.80 | 10.31 | 0.05 | 0.48 | 0.55 | 0.27 | 1.34 | - | 11.65 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 17 Lighting System | | | | | | | | | | | | | | | | |
| 1 | | | 01 Front Lighting | 9.43 | 0.61 | 2.04 | 12.08 | 0.06 | 0.56 | 0.64 | 0.32 | 1.57 | - | 13.65 | - | - | - |
| 2 | | | 02 Interior Lighting | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Rear Lighting | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 Special Mechanisms | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 Lighting Switches | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 9.43 | 0.61 | 2.04 | 12.08 | 0.06 | 0.56 | 0.64 | 0.32 | 1.57 | - | 13.65 | - | - | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 17 Lighting System | | | | | | | | | | | | | | | | |
| 1 | | | 01 Front Lighting | (3.07) | 0.54 | 0.76 | (1.77) | (0.01) | (0.08) | (0.09) | (0.05) | (0.23) | - | (2.00) | - | - | - |
| 2 | | | 02 Interior Lighting | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 Rear Lighting | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 Special Mechanisms | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 Lighting Switches | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | (3.07) | 0.54 | 0.76 | (1.77) | (0.01) | (0.08) | (0.09) | (0.05) | (0.23) | - | (2.00) | - | - | - |

### 7.1.19 Electrical Distribution and Electronic Control System

**Table 7.1-19: Electrical Distribution and Electronic Control System CMATs**

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | BASE TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 18 Electrical Distribution and Electronic Control System | | | | | | | | | | | | | | | | |
| 1 | | | 01 Electrical Wiring and Circuit Protection Subsystem | 95.83 | 0.67 | 1.13 | 97.63 | 0.41 | 8.03 | 5.41 | 0.72 | 14.57 | - | 112.20 | - | 318.50 | - |
| 2 | | | 02 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 95.83 | 0.67 | 1.13 | 97.63 | 0.41 | 8.03 | 5.41 | 0.72 | 14.57 | - | 112.20 | - | 318.50 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | COMPOUNDED TECHNOLOGY GENERAL PART INFORMATION: ??? | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 18 Electrical Distribution and Electronic Control System | | | | | | | | | | | | | | | | |
| 1 | | | 01 Electrical Wiring and Circuit Protection Subsystem | 42.28 | (4.33) | 6.14 | 44.09 | 0.19 | 3.64 | 2.49 | 0.35 | 6.66 | - | 50.75 | - | 90.13 | - |
| 2 | | | 02 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 42.28 | (4.33) | 6.14 | 44.09 | 0.19 | 3.64 | 2.49 | 0.35 | 6.66 | - | 50.75 | - | 90.13 | - |

| SYSTEM & SUBSYSTEM DESCRIPTION | | | | INCREMENTAL COST TO UPGRADE TO NEW TECHNOLOGY PACKAGE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Manufacturing | | | | Markup | | | | | | | | | |
| Item | System | Subsystem | Name/Description | Material | Labor | Burden | Total Manufacturing Cost (Component/ Assembly) | End Item Scrap | SG&A | Profit | ED&T-R&D | Total Markup Cost (Component/ Assembly) | Total Packaging Cost (Component/ Assembly) | Net Component/ Assembly Cost Impact to OEM | System ED&T/R&D (x1000) | Tooling (x1000) | Investment (X1000) |
| | | | | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD | USD |
| | 18 Electrical Distribution and Electronic Control System | | | | | | | | | | | | | | | | |
| 1 | | | 01 Electrical Wiring and Circuit Protection Subsystem | 53.55 | 5.00 | (5.00) | 53.54 | 0.22 | 4.39 | 2.92 | 0.37 | 7.90 | - | 61.44 | - | 228.38 | - |
| 2 | | | 02 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3 | | | 03 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4 | | | 04 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5 | | | 05 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | | | 06 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | | | 07 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 8 | | | 08 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 9 | | | 09 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 10 | | | 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| | | | SUBSYSTEM ROLL-UP | 53.55 | 5.00 | (5.00) | 53.54 | 0.22 | 4.39 | 2.92 | 0.37 | 7.90 | - | 61.44 | - | 228.38 | - |

## 7.2 Body and Frame Supporting Data

### 7.2.1 Vehicle Scan Data – Disassembled Parts

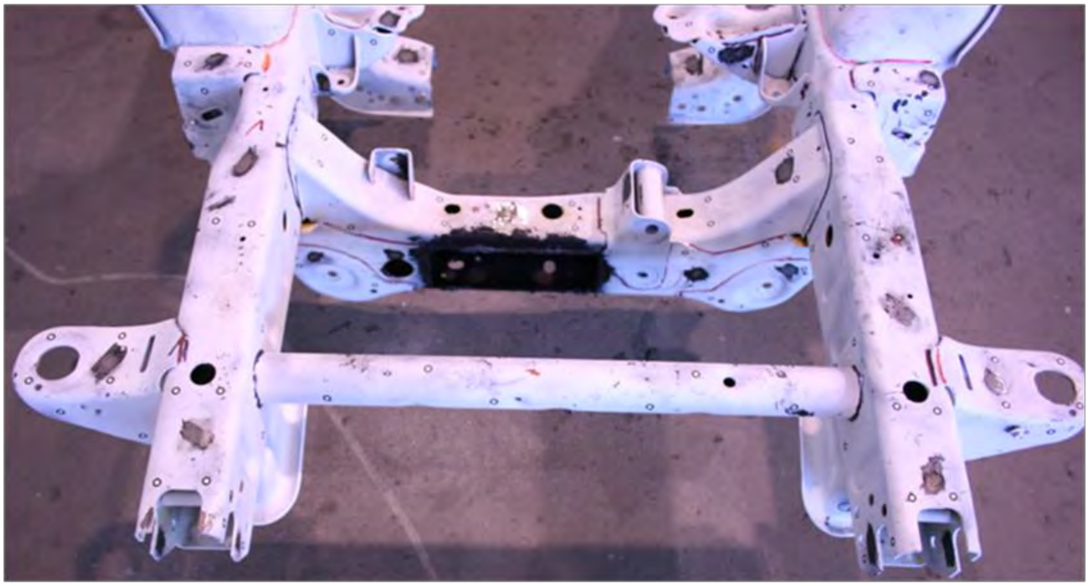

**Image 7.2-1: Front Rail Assembly**
*(Source: EDAG)*

**Image 7.2-2: Mid Rail Assembly**
*(Source: EDAG)*

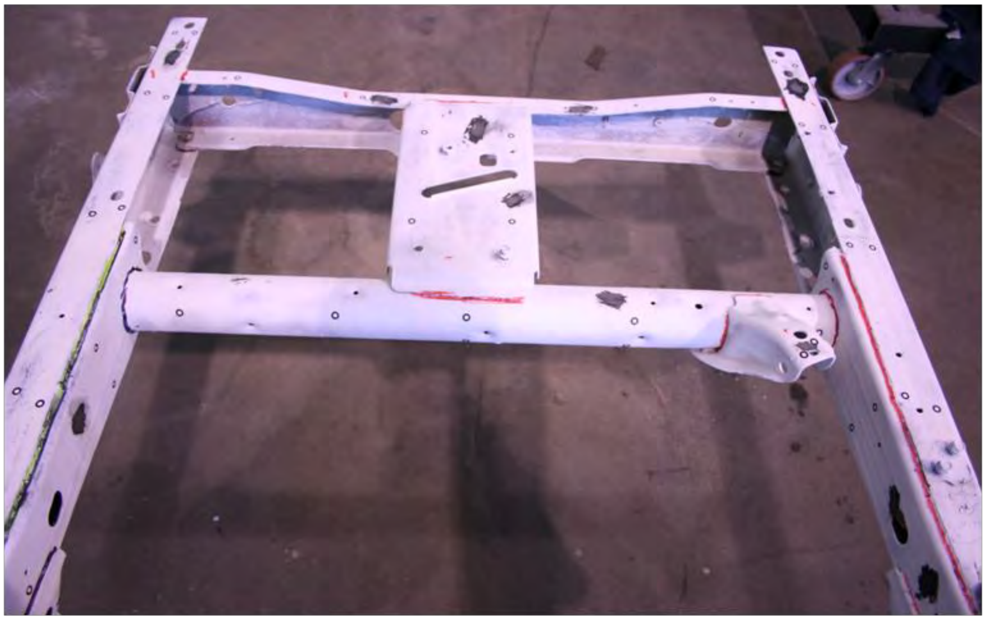

**Image 7.2-3: Rear Rail Assembly**
*(Source: EDAG)*

**Image 7.2-4: Front Shock Tower Assembly**
*(Source: EDAG)*

**Image 7.2-5: Cross Members Assembly**
*(Source: EDAG)*

**Image 7.2-6: Cross Members Assembly**
*(Source: EDAG)*


**Image 7.2-7: Cabin Assembly**
*(Source: EDAG)*


**Image 7.2-8: Cargo Box Assembly**
*(Source: EDAG)*

### 7.2.2 Scan Data from White Light Scanning

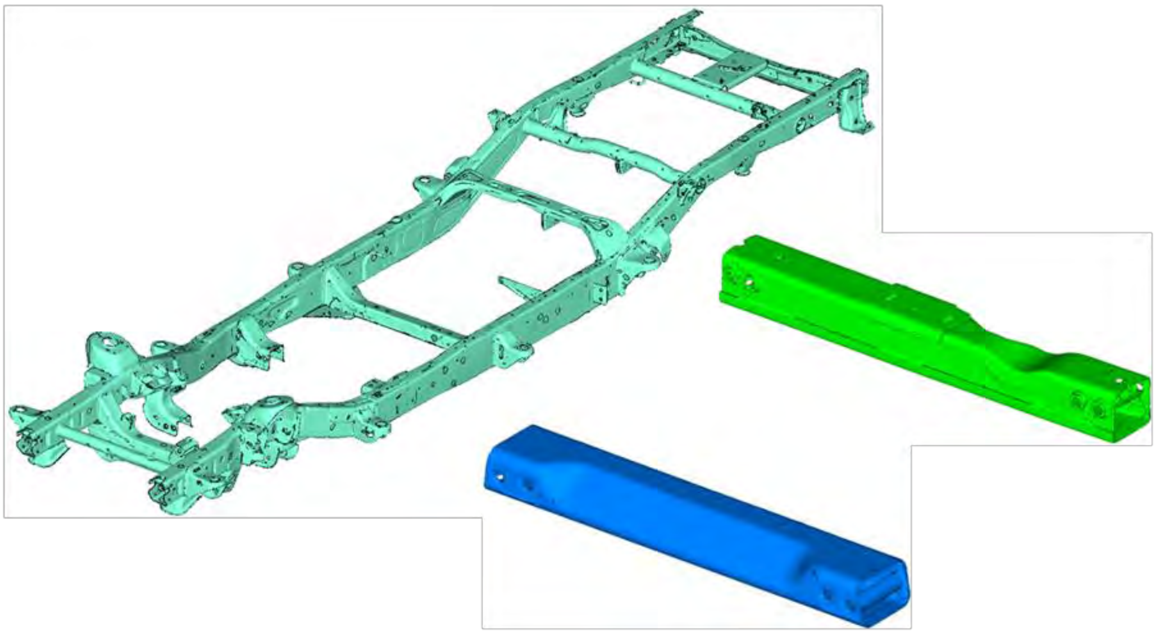

**Figure 7.2-1: STL Data Samples of Frame Assembly**
*(Source: EDAG)*

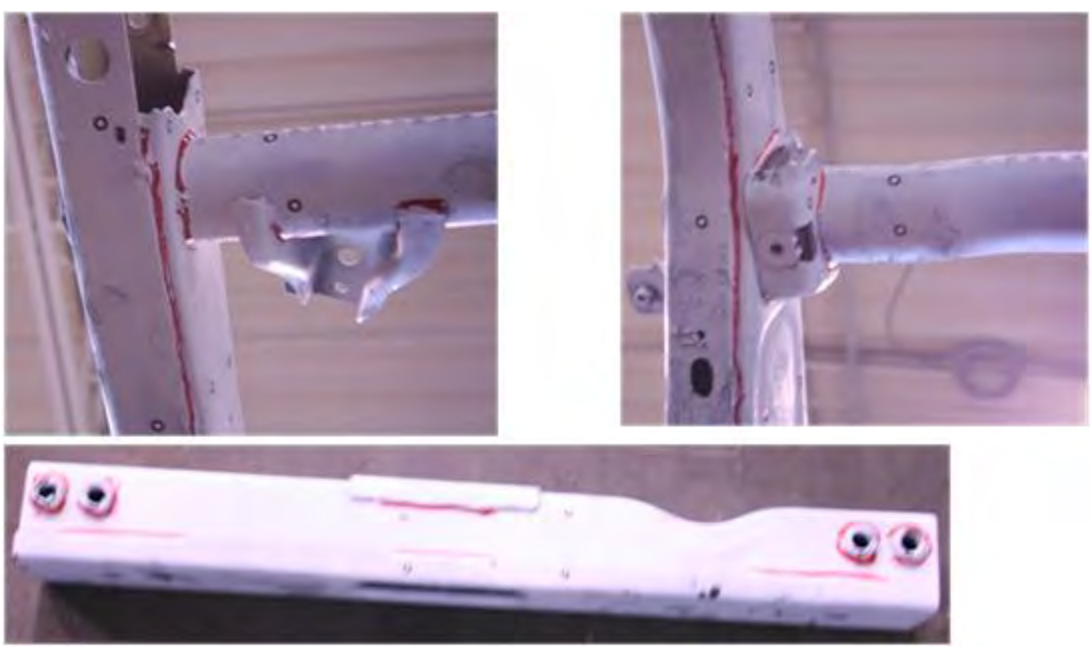

**Image 7.2-9: Weld Data from Scanning Process**
*(Source: EDAG)*

### 7.2.3 Material Models (LS-DYNA)

**Steel Material Models**

The structural steel materials used in the study are detailed in **Table 7.2-1**. *MAT_PIECEWISE_LINEAR_PLASTICITY (MAT_24) is used to represent the material with a table of stress strain curves at various strain rates (with VP=1 strain rate option). No damage or failure models are implemented in the material models.

**Table 7.2-1: Table of Common Engineering Properties [56]**

| Steel Grade | Density (t/mm$^3$) | Poisson's ratio | Modulus of Elasticity (MPa) | Lower YS (MPa) | Ultimate Tensile Strength (MPa) | Tot EL (%) |
|---|---|---|---|---|---|---|
| Mild 140/270 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 140 | 270 | 42-48 |
| Mild BH210/340 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 210 | 340 | 35-41 |
| Mild BH260/370 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 260 | 370 | 32-36 |
| DP 300/500 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 300 | 500 | 30-34 |
| HSLA 350/450 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 350 | 450 | 23-27 |
| DP 350/600 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 350 | 600 | 24-30 |
| DP 500/800 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 500 | 800 | 14-20 |
| DP 700/1000 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 700 | 1000 | 12-17 |
| CP 800/1000 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 800 | 1000 | 8-13 |
| MS 950/1200 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 950 | 1250 | 5-7 |
| CP 1050/1470 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 1050 | 1470 | 7-9 |
| HF 1050/1500 | 7.850e-09 | 0.3 | $21.0 \times 10^4$ | 1050 | 1500 | 5-7 |

56 WorldAutoSteel, the automotive group of the World Steel Association; http://worldautosteel.org/

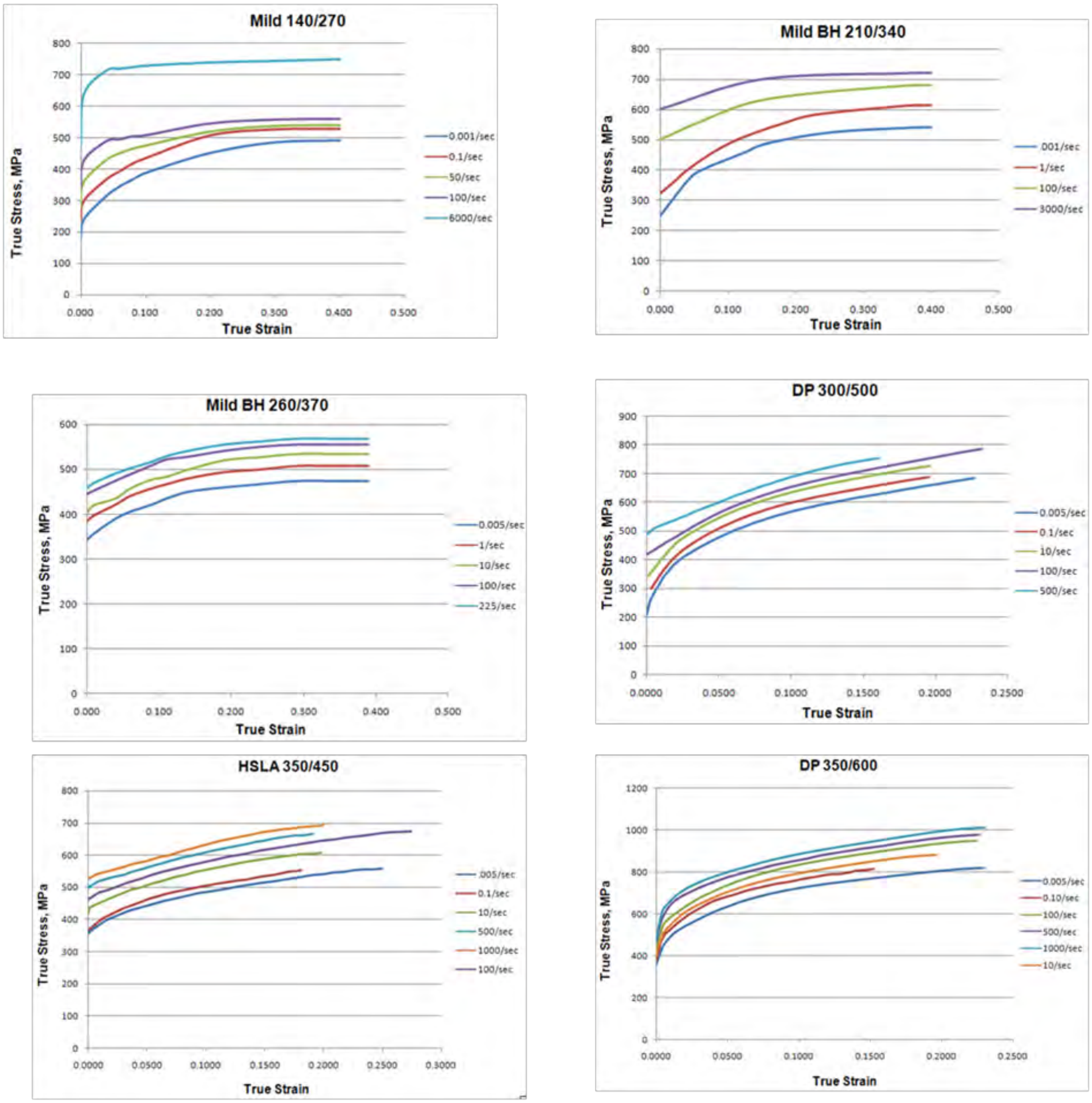


**Figure 7.2-2: Material Curves of Stress vs. Strain**

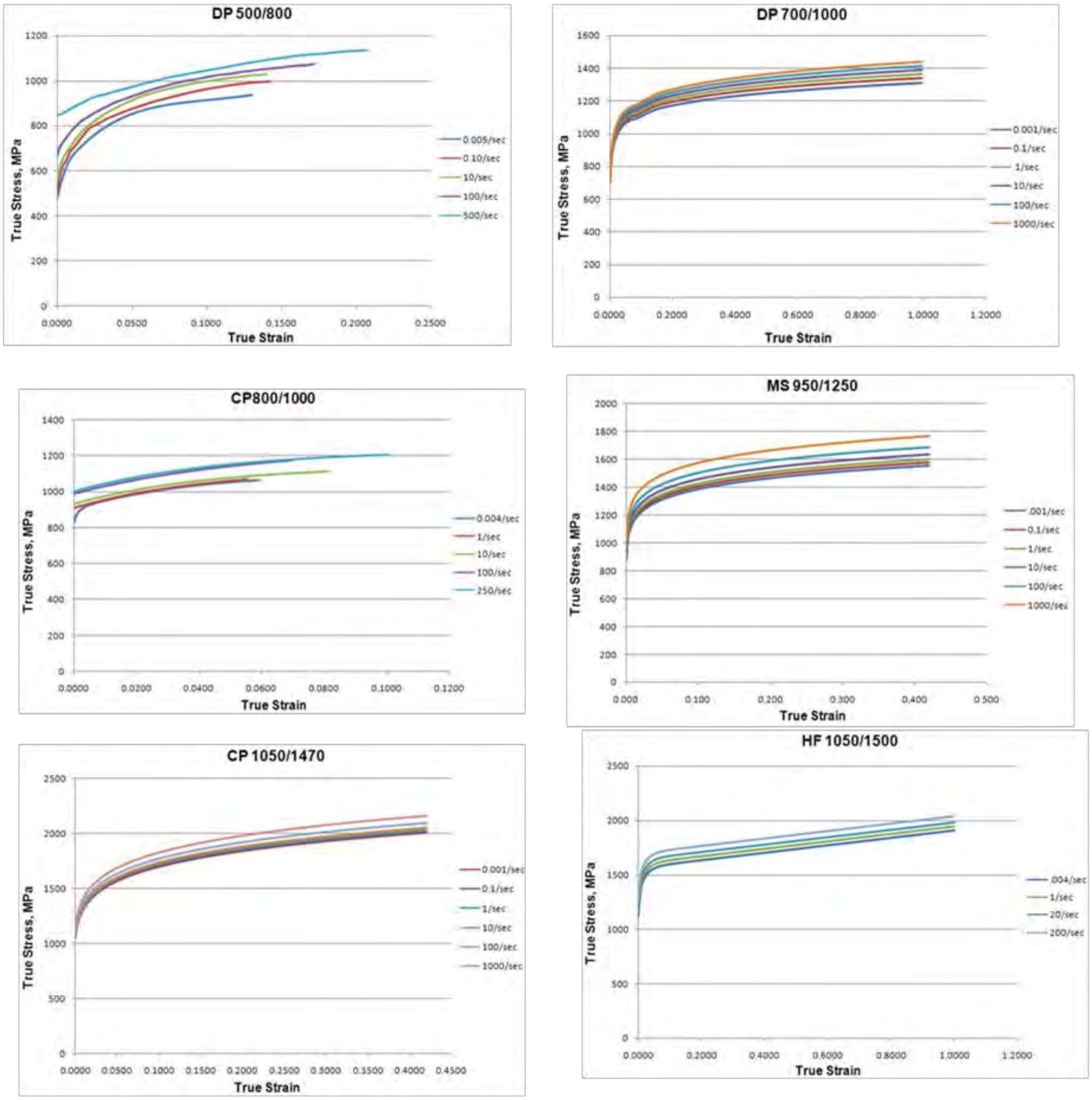


**Figure 7.2-3: Material Curves of Stress vs. Strain**

**Table 7.2-2: Material Curves of Stress vs. Strain (Aluminum)**

| Steel Grade | Density ($t/mm^3$) | Poisson's ratio | Modulus of Elasticity (MPa) | Lower YS (MPa) | Ultimate Tensile Strength (MPa) | Tot EL (%) |
|---|---|---|---|---|---|---|
| 5754 Aluminum | 2.7E-9 | 0.28 | 7.0 x 104 | 117 | 283 | 26.0 |
| Cast Aluminum | 2.7E-9 | 0.28 | 7.0 x 104 | 160 | 246 | 10.0 |
| 6082 T6 Aluminum | 2.71E-9 | 0.33 | 7.1 x 104 | 321 | 370 | 5.8 |

### 7.2.4 Load Path Analysis

In order to determine which components are the main contributors to the crash load path, 45 major section forces were measured in the five crash load cases.

**Figure 7.2-4** through **Figure 7.2-8** show the sectional force dominated parts in the five crash loadcases of the baseline model. The section force of each part cross section was calculated from the corresponding loadcases. The force level was shown as bar chart to see the significance of each loadcase in **Figure 7.2-9**.

Higher section force means the components are important in load path transfer in each crash events. Since optimization process requires one single CAE model to iterate all loadcases simultaneously. So section force should be combined into as one loadcases and the magnitude of each section force should be normalized as combined section divided with five maximum section force of each loadcase.

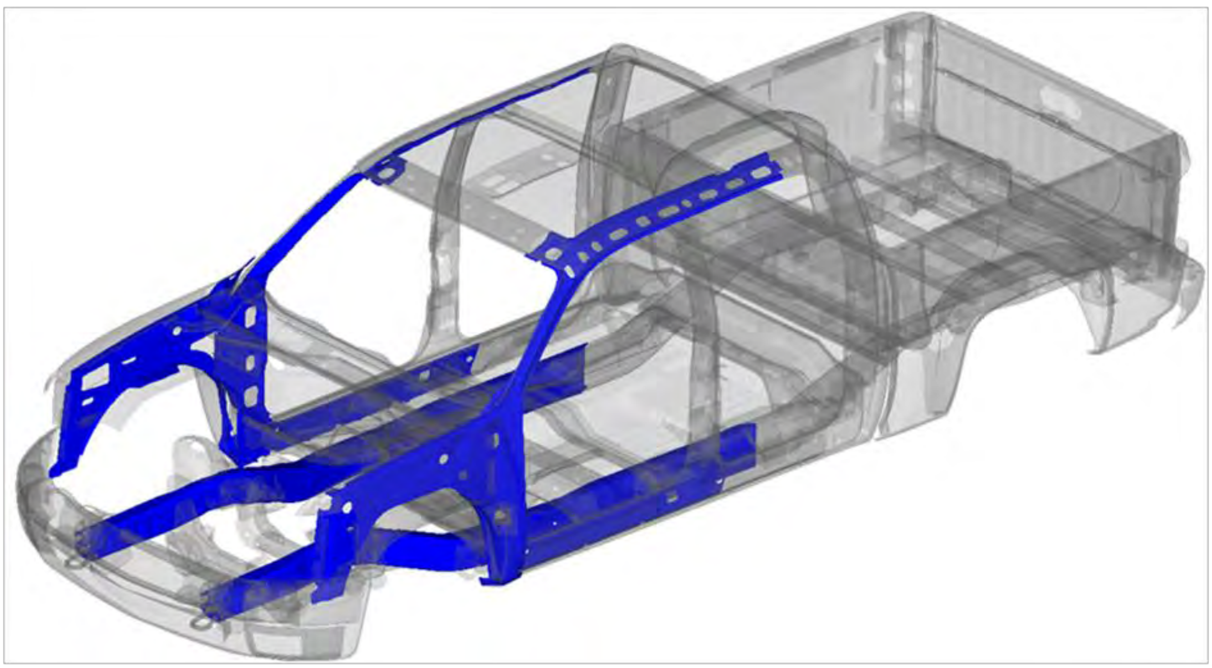

**Figure 7.2-4: Section Force of Baseline Model in Front Crash**

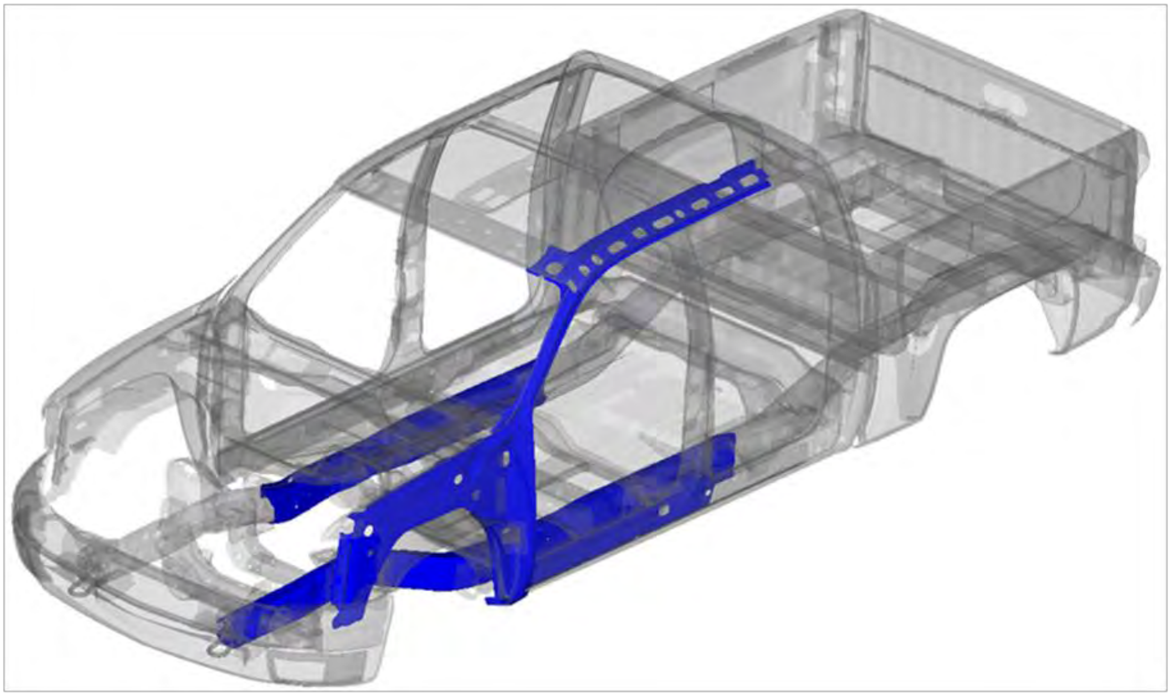

**Figure 7.2-5: Section Force of Baseline Model in Front Offset Crash**

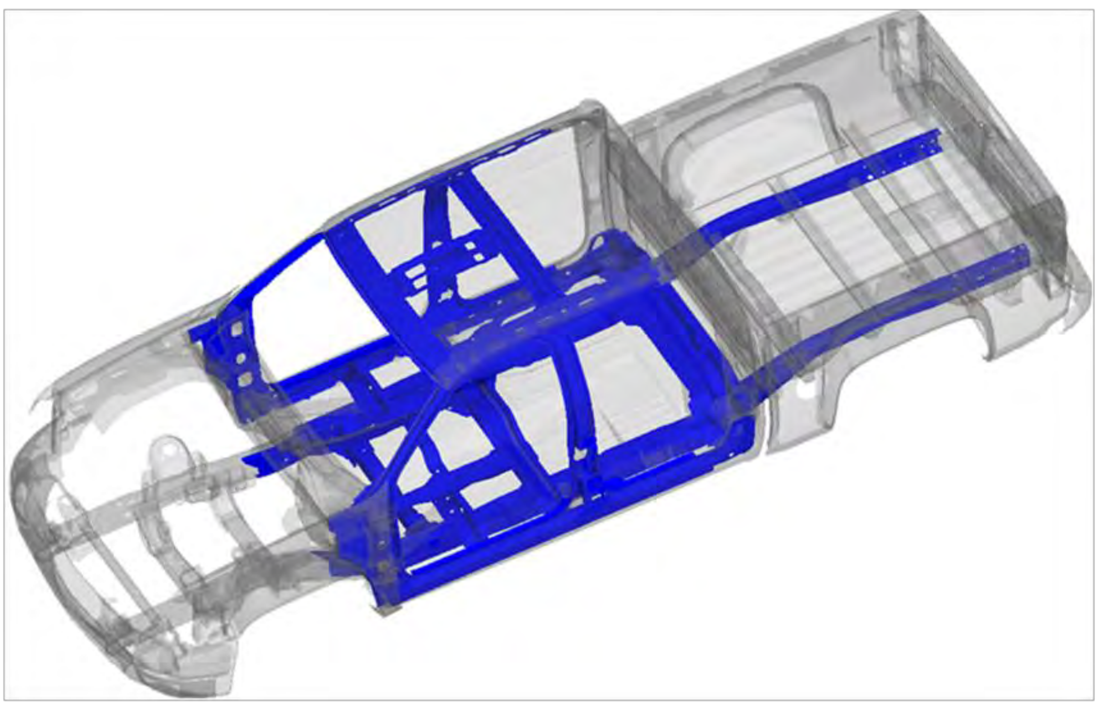

**Figure 7.2-6: Section Force of Baseline Model in Side Crash**

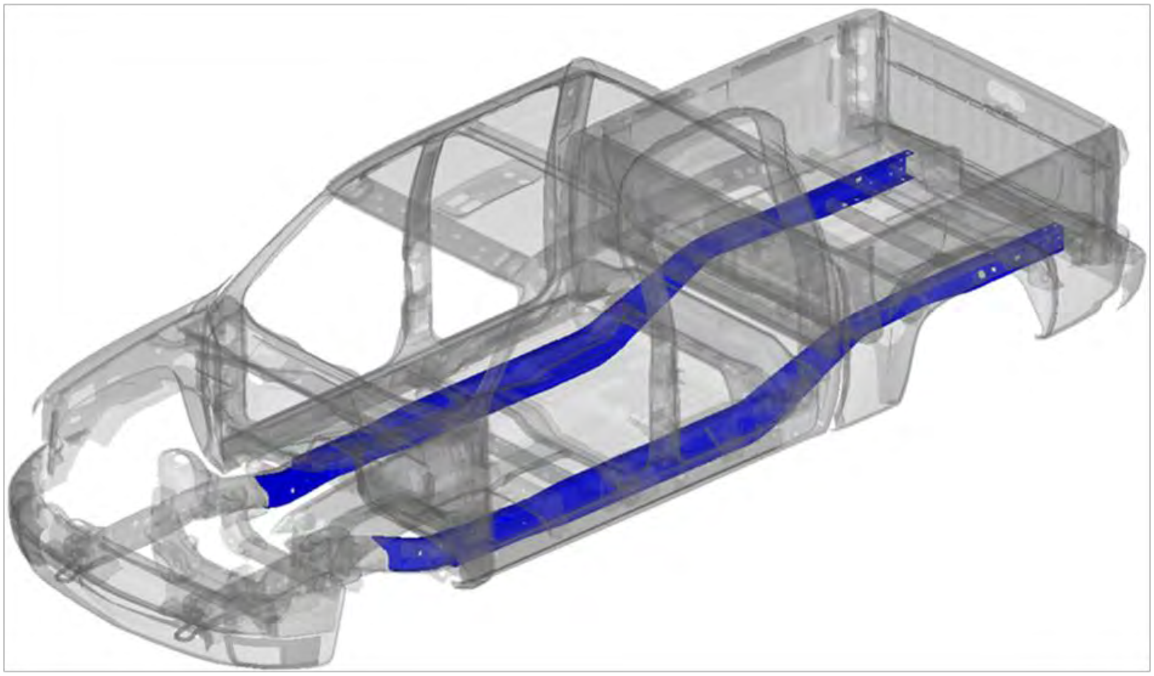

**Figure 7.2-7: Section Force of Baseline Model in Rear Crash**

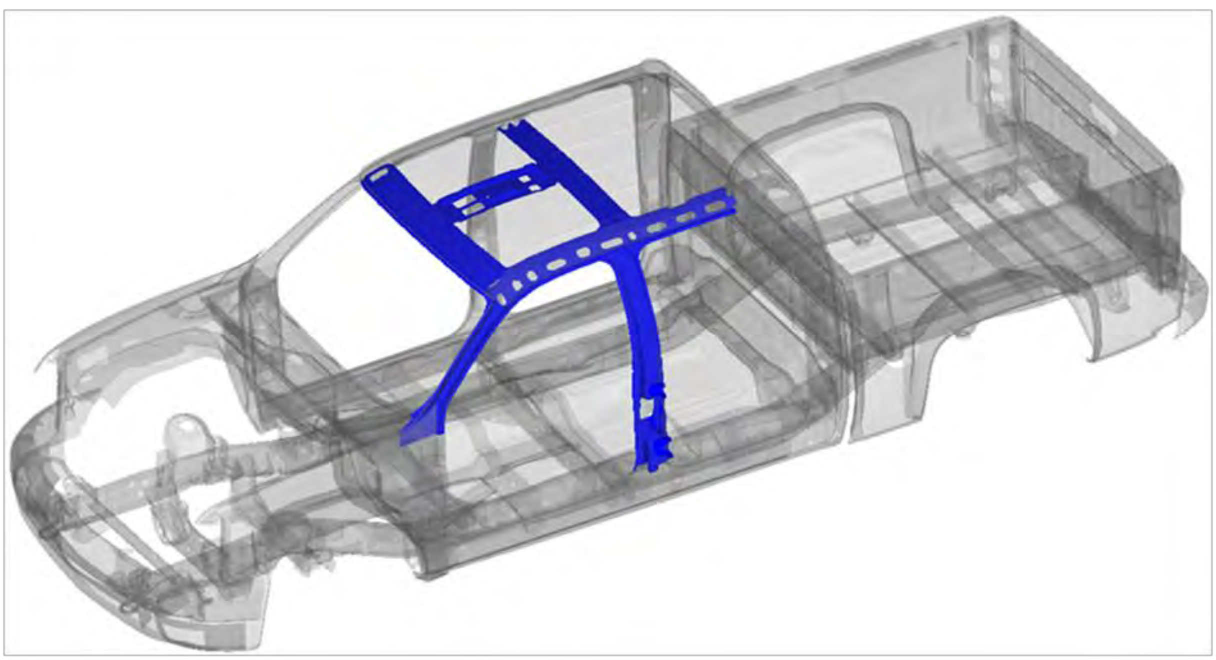

**Figure 7.2-8: Section Force of Baseline Model in Roof Crush**

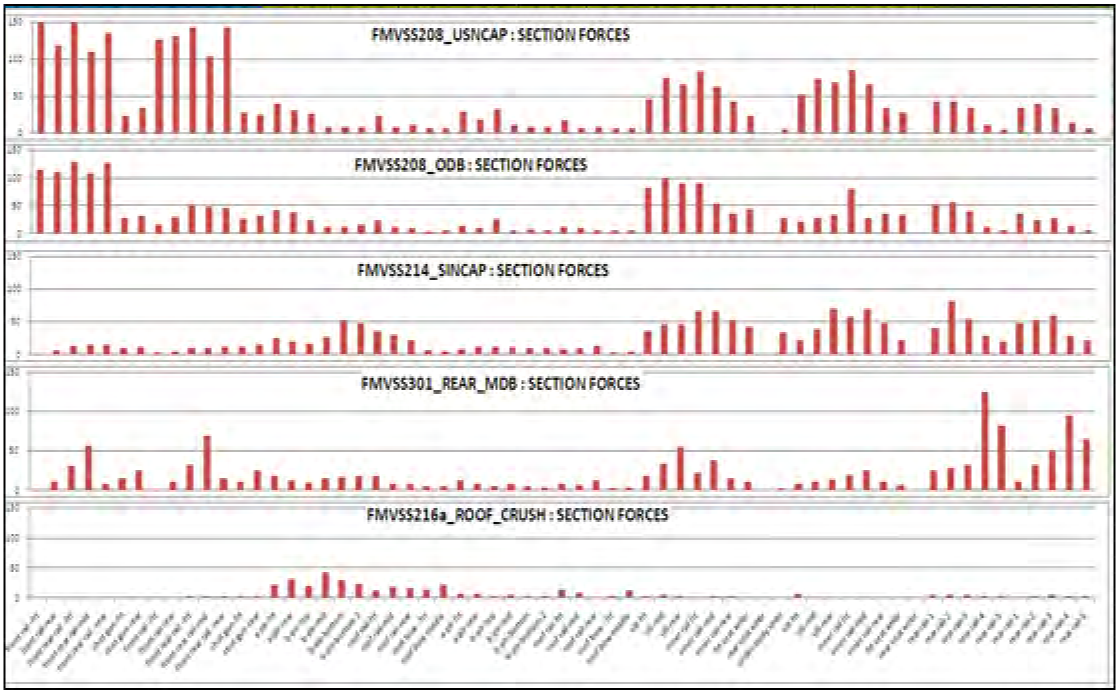


**Figure 7.2-9: Section Force Bar Chart**

As shown in **Figure 7.2-10,** the corresponding components of highlighted area in the normalized section force chart were considered as primary target parts.

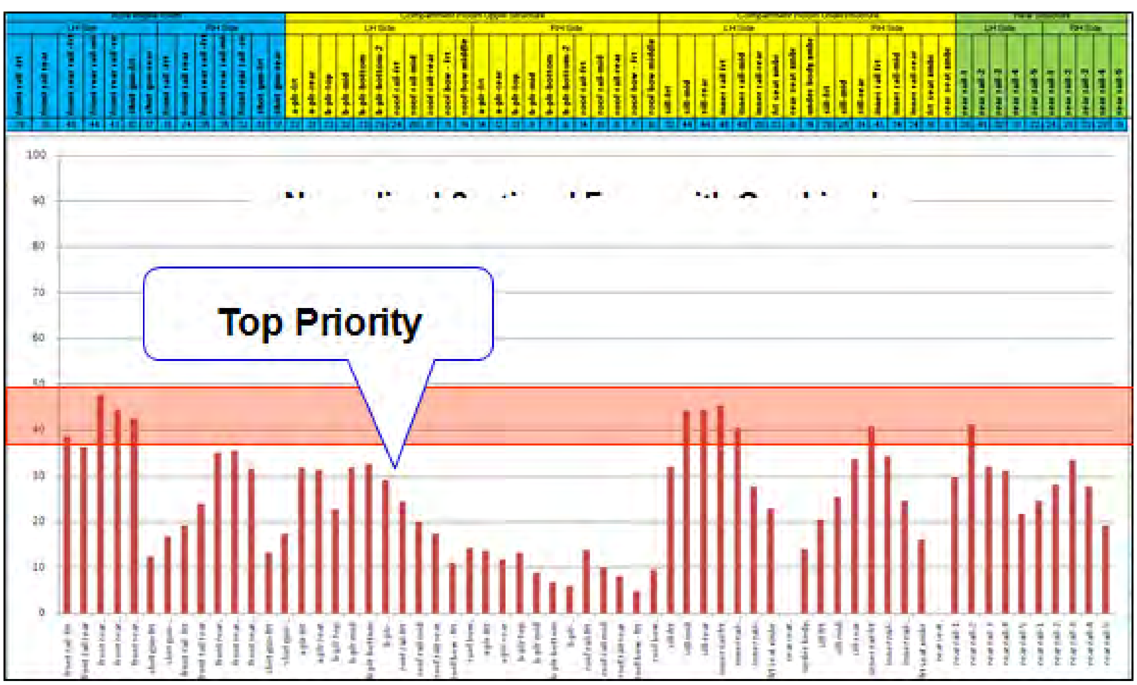


**Figure 7.2-10: Normalized Combined Sectional Force Bar Chart**

### 7.2.5 Subsystem Weight Reductions

| Legend | |
|---|---|
| ◆ | Baseline |
| ■ | Gauge and Grade |
| ▲ | 2 + Eng. Expertise |
| x | Gauge Opt |
| ✳ | TRB and Laser Weld |
| ● | Design changes |
| + | Aluminum/Magnesium |

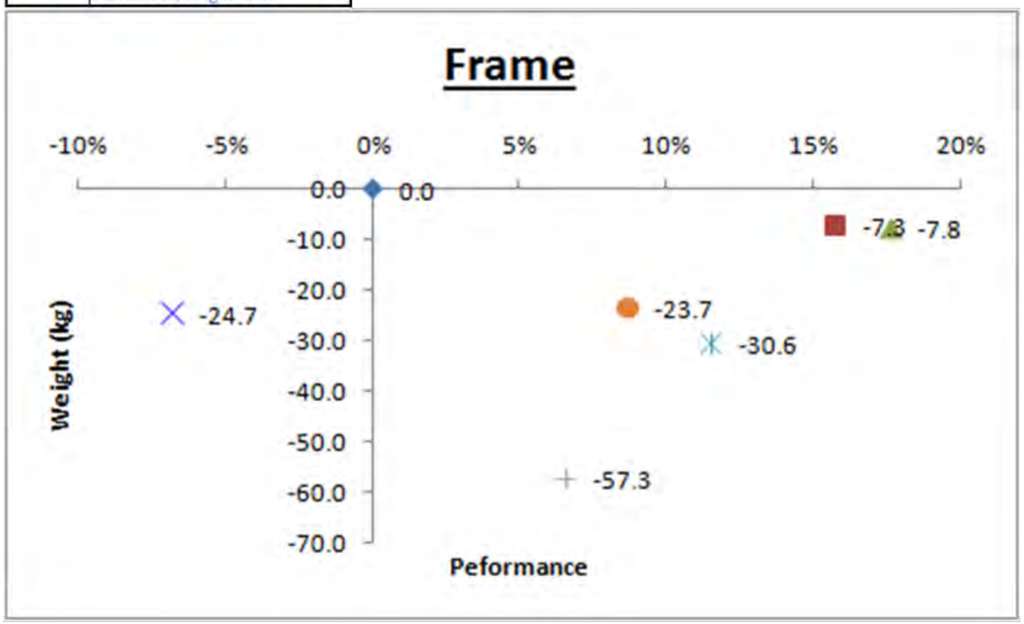


**Figure 7.2-11: Weight Reduction of Frame**

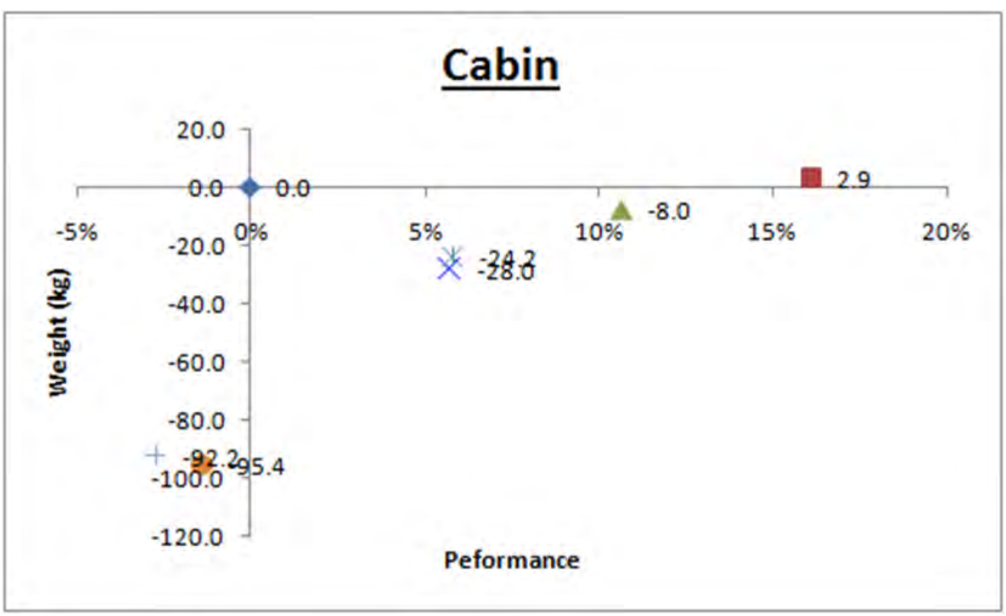


**Figure 7.2-12: Weight Reduction of Cabin**

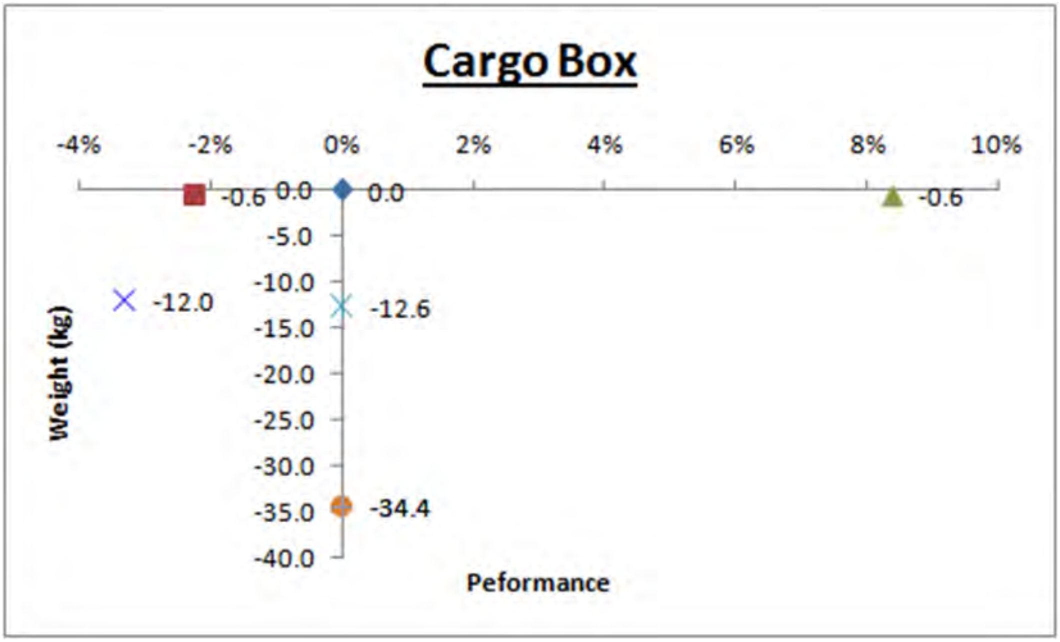


**Figure 7.2-13: Weight Reduction of Cargo Box**

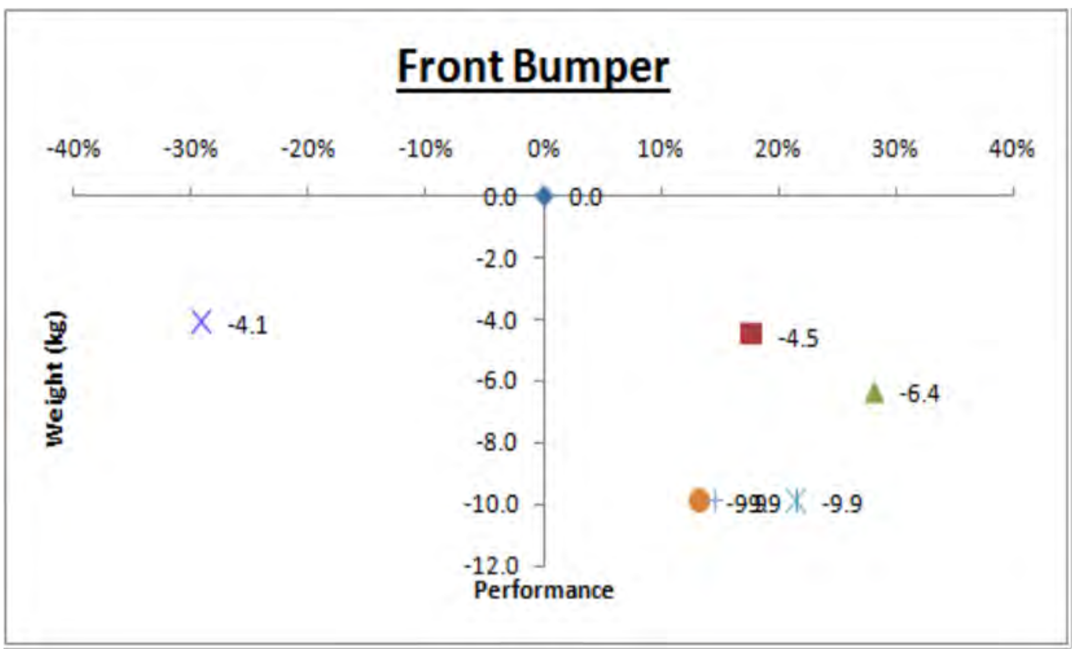


**Figure 7.2-14: Weight Reduction of Front Bumper**

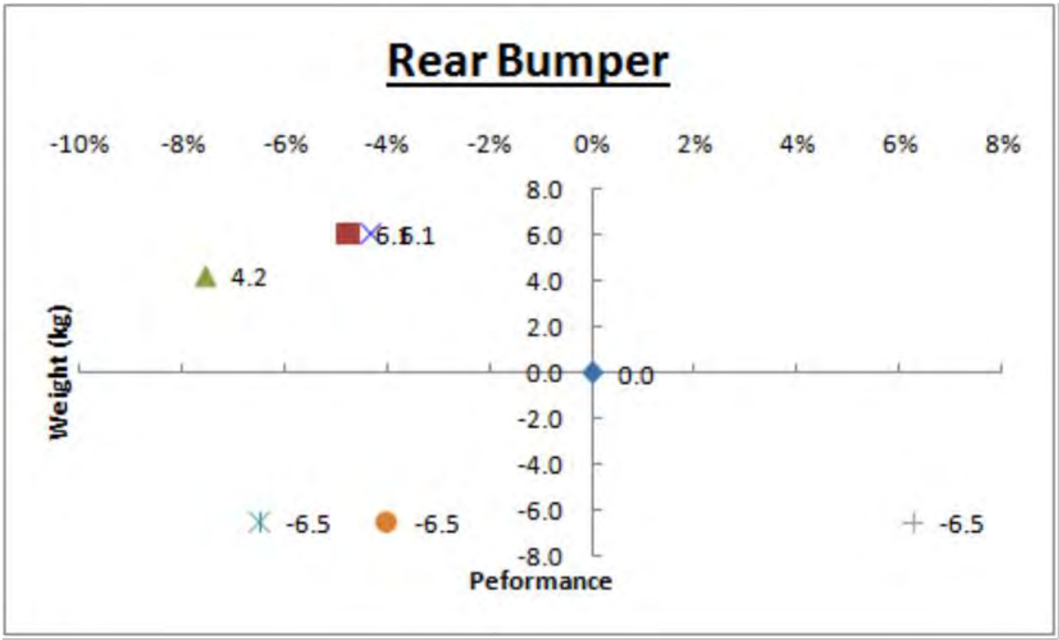


**Figure 7.2-15: Weight Reduction of Rear Bumper**

### 7.2.6 LS-DYNA Model Development

For future development of the Silverado LS-DYNA model the following areas of the model can be further improved. In most cases this will also require a new test program to provide the necessary information.

Update the model to a full 2011 4WD configuration

Update the cabin to be fully representative of the 2011 4WD model

Update the powertrain mounts (material models for rubber and detailed modeling of the mounts)

Update the Body to Frame rubber mounts with complete static and dynamic mount performance and attaching bolt preload test data (to allow compliance and damage)

Update the front and rear prop shaft models with failure load data

Implement damage and failure models for sheet metal in highly loaded regions

Implement failure model for spot-welds and rivets

### 7.2.7 FEV Mass Optimized Systems

As part of the study FEV has looked at mass reduction in the chassis and powertrain systems. The output of the study was a new mass for each system with no redesign of the system or part being performed.

For the crashworthiness study the mass of each system was tuned via density / lumped mass (along with reduced Young's Modulus in some cases) to ballast the system models to the new target mass.

Some of the components provide a major load path in the crashworthiness loadcases and would require a complete redesign to perform with the new material which was outside of the scope of this project. The systems detailed below have the potential to have an influence on the crash performance (with the possibility of new failure modes being introduced)

Rear Leaf springs (steel to composite) – large deformation in the rear impact 301 simulation.

Chassis components (steel to aluminum) –control arms, axles

### 7.2.8 Key Updates from the 2007-2011 CAE Model Implemented

**1) Frame (2011AWD)**

The frame was scanned /modeled and meshed in full to create an updated model.

**2) Cab – updates to welds**

The cab was inspected visually and the weld positions updated in some areas

**3) Tow bar**

The tow bar was scanned/modeled and meshed in full to create a new updated model.

**4) 4x4 Driveline components**

The transfer case, front driveshaft, rear driveshaft, front brake calipers, front differential and drive axles were modeled and added to the model.

**5) Mass distribution (as per 2011 AWD)**

The mass distribution was taken from the FEV teardown data and distributed into the LS-DYNA model onto the existing components.

### 7.2.9 Cost Assumptions

**Table 7.2-3: Part Process Data for Cost Estimation**

| Part Size | Material | Thickness | Scrap Percentage | Blank Mass (kg) | Blank Surface Area | Cycle time | Eqpmnt. Invest |
|---|---|---|---|---|---|---|---|
| 6-Large Panel | Cold Rolled Reference -Mild 140/270 | 0.99 | 0.65 | 29.81352 | 3836263.27 | 400 | Transfer1-1400 |
| 6-Large Panel | Cold Rolled Reference -Mild 140/270 | 0.85 | 0.65 | 17.697075 | 2652240.54 | 400 | Transfer1-1400 |
| 4-Medium High Complex | Cold Rolled Reference -Mild 140/270 | 1.82 | 0.65 | 3.3797445 | 236560.8245 | 450 | Tandem3-600 |
| 6-Large Panel | Cold Rolled Reference -Mild 140/270 | 0.97 | 0.65 | 17.60022 | 2311408.497 | 400 | Transfer1-1400 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.51 | 0.55 | 2.3880385 | 201462.7325 | 500 | Tandem1-350 |
| 6-Large Panel | Cold Rolled Reference -Mild 140/270 | 0.85 | 0.65 | 18.011235 | 2699323.342 | 400 | Transfer1-1400 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 0.99 | 0.55 | 0.71211185 | 91631.19732 | 500 | Tandem1-350 |
| 4-Medium High Complex | Cold Rolled Reference -Mild 140/270 | 1.82 | 0.65 | 3.3794145 | 236537.7266 | 450 | Tandem3-600 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.53 | 0.55 | 5.1314145 | 427244.0365 | 500 | Tandem1-350 |
| 6-Large Panel | DP 300/500 | 0.99 | 0.65 | 14.7011535 | 1891675.159 | 400 | Transfer1-1400 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 0.73 | 0.55 | 1.50692395 | 262965.5266 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 0.7 | 0.55 | 1.3577442 | 247087.2066 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.53 | 0.55 | 1.82652 | 152076.9327 | 500 | Tandem1-350 |
| 2-Small | Cold Rolled Reference -Mild 140/270 | 1.01 | 0.3 | 0.3042494 | 38374.14391 | 1200 | Progressive1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 2.16 | 0.55 | 0.52861045 | 31175.42168 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 0.73 | 0.55 | 1.8053625 | 315044.4987 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 0.73 | 0.55 | 1.50682785 | 262948.7567 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 0.73 | 0.55 | 1.8053935 | 315049.9084 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 0.7 | 0.55 | 1.35791315 | 247117.9527 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.21 | 0.55 | 1.2417267 | 130728.7151 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.53 | 0.55 | 1.826551 | 152079.5138 | 500 | Tandem1-350 |
| 2-Small | Cold Rolled Reference -Mild 140/270 | 1.01 | 0.3 | 0.3040518 | 38349.22116 | 1200 | Progressive1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 2.16 | 0.55 | 0.52862595 | 31176.33581 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.5 | 0.55 | 3.979563 | 337967.1338 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.52 | 0.55 | 4.9270315 | 412925.8716 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 0.99 | 0.55 | 0.7119646 | 91612.24989 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.21 | 0.55 | 1.24150195 | 130705.0534 | 500 | Tandem1-350 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.51 | 0.55 | 2.3879765 | 201457.502 | 500 | Tandem1-350 |
| 6-Large Panel | Cold Rolled Reference -Mild 140/270 | 0.97 | 0.65 | 17.60418 | 2311928.557 | 400 | Transfer1-1400 |
| 4-Medium High Complex | Cold Rolled Reference -Mild 140/270 | 1.59 | 0.65 | 9.4176555 | 754529.1431 | 450 | Tandem3-600 |
| 3-Medium Low Complex | Cold Rolled Reference -Mild 140/270 | 1.51 | 0.55 | 6.707501 | 565866.706 | 500 | Tandem1-350 |

## Table 7.2-4: Material Price

| Item # | Steel Grade | Ref Material Price ($/kg) | Grade Premium ($/kg) | HDG Premium ($/kg) | Exposed Premium ($/kg) | Tailor Rolled Coil Premium ($/kg) | Tubes (straight, as shipped) Premium ($/kg) | Multiwall Tube Blank Premium ($/kg) | Tool Investment Factor | Line Rate Factor | Reject Rate Factor |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Reference US Spot Midwest Market Price Trend 2009 | | | | | | | | | | |
| | Cold Rolled Reference -Mild 140/270 | 0.93 | 0.00 | 0.06 | 0.05 | 0.55 | 0.25 | 0.65 | 1.0 | 1.0 | 1.0 |
| 2 | BH 210/340 | 0.98 | 0.05 | 0.06 | 0.10 | 0.55 | 0.25 | 0.65 | 1.05 | 0.95 | 1.05 |
| 3 | BH 260/370 | 0.98 | 0.05 | 0.06 | 0.10 | 0.55 | 0.25 | 0.65 | 1.05 | 0.95 | 1.05 |
| 4 | BH 280/400 | 1.00 | 0.07 | 0.06 | 0.10 | 0.55 | 0.30 | 1.10 | 1.05 | 0.95 | 1.05 |
| 5 | IF 260/410 | 1.00 | 0.07 | 0.00 | 0.10 | 0.55 | 0.30 | 0.70 | 1.05 | 0.95 | 1.05 |
| 6 | IF 300/420 | 1.03 | 0.10 | 0.00 | 0.10 | 0.55 | 0.30 | 1.10 | 1.05 | 0.95 | 1.05 |
| 7 | HSLA 350/450 | 1.05 | 0.12 | 0.10 | NA | 0.55 | 0.30 | 1.50 | 1.05 | 0.95 | 1.05 |
| 8 | HSLA 420/500 | 1.07 | 0.14 | 0.10 | NA | 0.55 | 0.45 | 1.25 | 1.10 | 0.90 | 1.10 |
| 9 | HSLA 490/600 | 1.09 | 0.16 | 0.10 | NA | 0.55 | 0.45 | 1.65 | 1.10 | 0.90 | 1.10 |
| 10 | HSLA 550/650 | 1.28 | 0.35 | 0.10 | NA | 0.55 | 0.45 | 1.65 | 1.10 | 0.90 | 1.10 |
| 12 | SF 570/640 | 1.28 | 0.35 | 0.10 | NA | NA | 0.45 | 2.05 | 1.10 | 0.90 | 1.10 |
| 13 | SF 600/780 | 1.28 | 0.35 | 0.10 | NA | NA | 0.45 | 2.05 | 1.10 | 0.90 | 1.10 |
| 14 | TRIP 350/600 | 1.33 | 0.40 | 0.10 | NA | NA | 0.45 | 1.25 | 1.10 | 0.90 | 1.10 |
| 15 | TRIP 400/700 | 1.38 | 0.45 | 0.10 | NA | NA | 0.45 | 1.65 | 1.10 | 0.90 | 1.10 |
| 16 | TRIP 450/800 | 1.43 | 0.50 | 0.10 | NA | NA | 0.50 | 1.30 | 1.15 | 0.85 | 1.15 |
| 17 | TRIP 600/980 | 1.48 | 0.55 | 0.10 | NA | NA | 0.55 | 1.35 | 1.15 | 0.85 | 1.15 |
| 18 | FB 330/450 | 1.13 | 0.20 | 0.10 | NA | 0.55 | 0.30 | 1.10 | 1.05 | 0.95 | 1.05 |
| 19 | FB 450/600 | 1.18 | 0.25 | 0.10 | NA | 0.55 | 0.45 | 1.65 | 1.10 | 0.90 | 1.10 |
| 20 | DP 300/500 | 1.13 | 0.20 | 0.10 | 0.10 | 0.55 | 0.45 | 0.85 | 1.10 | 0.90 | 1.10 |
| 21 | DP 350/600 | 1.19 | 0.26 | 0.10 | 0.10 | 0.55 | 0.45 | 1.25 | 1.10 | 0.90 | 1.10 |
| 22 | DP 500/800 | 1.24 | 0.31 | 0.10 | NA | 0.55 | 0.50 | 0.90 | 1.15 | 0.85 | 1.15 |
| 23 | DP 700/1000 | 1.31 | 0.38 | 0.10 | NA | NA | 0.55 | 0.95 | 1.15 | 0.85 | 1.15 |
| 25 | DP 1150/1270 | 1.31 | 0.38 | 0.10 | NA | NA | 0.55 | 0.95 | 1.15 | 0.85 | 1.15 |
| 26 | CP 500/800 | 1.24 | 0.31 | 0.10 | NA | NA | 0.50 | 1.30 | 1.15 | 0.85 | 1.15 |
| 27 | CP 600/900 | 1.28 | 0.35 | 0.10 | NA | NA | 0.52 | 1.32 | 1.15 | 0.85 | 1.15 |
| 28 | CP 750/900 | 1.33 | 0.40 | 0.10 | NA | NA | 0.52 | 1.32 | 1.15 | 0.85 | 1.15 |
| 29 | CP 800/1000 | 1.38 | 0.45 | 0.10 | NA | NA | 0.55 | 1.35 | 1.15 | 0.85 | 1.15 |
| 30 | CP 1000/1200 | 1.40 | 0.47 | 0.10 | NA | NA | 0.60 | 1.40 | 1.20 | 0.80 | 1.20 |
| 31 | CP 1050/1470 | 1.40 | 0.47 | 0.10 | NA | NA | 0.60 | 1.80 | 1.20 | 0.80 | 1.20 |
| 32 | MS 950/1200 | 1.40 | 0.47 | NA | NA | NA | 0.60 | 1.00 | 1.20 | 0.80 | 1.20 |
| 33 | MS 1150/1400 | 1.41 | 0.48 | NA | NA | NA | 0.60 | 1.40 | 1.20 | 0.80 | 1.20 |
| 34 | TWIP 500/980 | 2.13 | 1.20 | 0.10 | NA | NA | 0.60 | 1.80 | 1.20 | 0.80 | 1.20 |
| 35 | MS 1250/1500 | 1.44 | 0.51 | 0.10 | NA | NA | 0.65 | 1.05 | 1.20 | 0.80 | 1.20 |
| 36 | HF 1050/1500 (22MnB5) | 1.68 | 0.75 | NA | NA | 0.55 | 0.65 | 1.05 | 1.20 | 0.80 | 1.20 |
| | Base Aluminum | 2.20 | 0.00 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al 6111 Exposed | 4.29 | 2.09 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al 6111 | 4.29 | 2.09 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al 6061 | 4.29 | 2.09 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al 5454 | 3.85 | 1.65 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al 5182 | 3.85 | 1.65 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al 5754 | 3.85 | 1.65 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al 6022 | 4.29 | 2.09 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al 6082 | 4.29 | 2.09 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al 7000 | 4.68 | 2.48 | | | | | | 1.00 | 1.00 | 1.00 |
| | Al Sandcast (Generic) | 12.10 | 9.90 | | | | | | 1.00 | 1.00 | 1.00 |

***** Steel and Aluminum scrap prices of $0.22/kg and $2.00/kg respectively *****

**Table 7.2-5: Assumptions for Equipment, Building and Overhead Cost**

| Parameters | Assumptions | |
|---|---|---|
| Production Volume | 200,000 | per year |
| Annual Paid Time | 3600 | hours |
| Wage (Average) | 35 | $ USD/hr |
| Unit energy Cost | 0.07 | $ USD /kWh |
| Interest | 8% | |
| Equipment Life | 20 | years |
| Product Life | 5 | years |
| Building Life | 25 | years |
| Building unit cost | $1,500 | $ USD/sqm |
| Number of Indirect workers per direct worker | 0.25 | |
| Number of Indirect workers per line | 1 | |
| Number of Indirect workers per direct Assembly worker | 0.2 | |
| Number of Indirect workers per Assembly station | 0.125 | |
| CO2 (USA Electricity Production) | 833 | g/kWh |

**Table 7.2-6: Assumptions for Manufacturing Energy, Maintenance and Labor Cost**

| Parameters | Assumptions (Blanking) | Assumptions (Stamping) |
|---|---|---|
| Energy consumption rate | 150 kW/hr | 150 kW/hr |
| Space requirement | 100 sqm/line | 50 sqm/line |
| Manpower | 1 worker/line | part dependent |
| Unplanned downtime | 2 hrs/day | 3 hrs/day |
| Maintenance Percentage | 10% | 10% |
| Material loss percent | 1% | NA |
| Reject rate | 0.10% | part dependent |
| Press line die average change time | NA | |
| Press line lot size | NA | |

**Table 7.2-7: Assumptions for Manufacturing Labor Cost**

| Direct Labor Rate | Mean hourly wage | Benefits (41%) | Total |
|---|---|---|---|
| Stamping Press Operator | $24.69 | $10.12 | $34.81 |
| Blanking, Trimming | $15.84 | $6.49 | $22.33 |
| Heat Treat Operator | $16.71 | $6.85 | $23.56 |
| General Assembler | $22.54 | $9.24 | $31.78 |
| Die Cast Operator | $15.31 | $6.28 | $21.59 |
| Forging Operator | $15.66 | $6.42 | $22.08 |
| Rollforming Operator | $17.46 | $7.16 | $24.62 |
| Welding Operator | $15.72 | $6.45 | $22.17 |

**Table 7.2-8: Assumptions for Material Cost of Assembling**

| Assembly Process | Connect Rate (connects/ sec) | Joining Speed (m/sec) | Connect Spacing (meters) | Cycle Time (sec/cycle) | Power Requirement (kW or KWh/connect) | Electrode Life (meters or connects) | Electrode Cost ($/electrode) | Gas Use Rate (l/m or l/connect) | Gas Cost ($/l) | Adhesive Use Rate (kg/m or kg/connect) | Adhesive/Filler Cost ($/kg) | Fastener Cost ($/fastener) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1-Adhesive | | 0.3 | | 3.0 | 30.0 | | | | | 0.01 | 20.00 | |
| 2-Laser Braze | | 0.08 | | 3.0 | 115.0 | | | 0.33 | 0.02 | 0.30 | 0.90 | |
| 3-Laser - Robotic | | 0.08 | | 3.0 | 115.0 | | | 0.33 | 0.02 | | | |
| 4-Laser - Robotic (Large) | | 0.08 | | 3.0 | 115.0 | | | 0.33 | 0.02 | | | |
| 5-MIG | | 0.02 | | 4.0 | 33.0 | | | 20.0 | 0.01 | 0.30 | 1.00 | |
| 6-RSW - Small (static) | 0.5 | | 0.035 | 10.0 | 0.04 | 3000 | 0.45 | | | | | |
| 7-RSW | 1.0 | | 0.035 | 5.0 | 0.04 | 3000 | 0.45 | | | | | |
| 8-RSW (Medium) | 1.0 | | 0.035 | 5.0 | 0.04 | 3000 | 0.45 | | | | | |
| 9-RSW (Large) | 1.0 | | 0.035 | 5.0 | 0.04 | 3000 | 0.45 | | | | | |
| 10-Fastening | 0.2 | | | 5.0 | 0.02 | | | | | | | 0.10 |
| F0 - RSW (Framer) | 1.0 | | 0.04 | 5.0 | 0.10 | 6000 | 0.65 | | | | | |
| F1 - Laser (Framer) | | 0.07 | | 3.0 | 115.0 | | | | | | | |
| 13-Hemming | | 0.01 | | 4.0 | 0.50 | | | | | | | |
| 14-SPR (Rivet) | 0.2 | | 0.04 | 5.5 | 0.002 | | | | | | | 0.04 |

**Table 7.2-9: Assumptions for Labor and Equipment Cost of Assembling**

| Assembly Process | Assembly Equipment per station (#/station) | Unit Assembly Equipment cost ($/operator) | Idle Stations per Assembly | Idle Stations Cost | Labor Requirement (lab/Assembly Equipment) | Requires Fixture ($, 0-No) | Station Cost ($/station) | Requires Transport (Yes-1, No-0) | Station Space (sqm/station) | Additonal Equipment ($/station) |
|---|---|---|---|---|---|---|---|---|---|---|
| **1-Adhesive** | 3 | 125,000 | 1.000 | 25,000 | 0.25 | 120,000 | 20,000 | 1 | 100 | $50,000 |
| 2-Laser Braze | 2 | 600,000 | 1.000 | 25,000 | 0.25 | 1,500,000 | 50,000 | 1 | 100 | $910,000 |
| 3-Laser - Robotic | 2 | 500,000 | 1.000 | 25,000 | 0.25 | 150,000 | 50,000 | 1 | 100 | $400,000 |
| 4-Laser - Robotic (Large) | 8 | 500,000 | 1.000 | 25,000 | 0.25 | 1,500,000 | 50,000 | 1 | 200 | $600,000 |
| 5-MIG | 1 | 130,000 | 0.500 | 10,000 | 0.20 | 150,000 | 10,000 | 1 | 100 | $50,000 |
| 6-RSW - Small (static) | 2 | 30,000 | 0.170 | 10,000 | 0.50 | 50,000 | 20,000 | 1 | 50 | $50,000 |
| 7-RSW | 4 | 75,000 | 0.170 | 10,000 | 0.50 | 50,000 | 20,000 | 1 | 100 | $50,000 |
| 8-RSW (Medium) | 6 | 120,000 | 0.330 | 20,000 | 0.25 | 150,000 | 20,000 | 1 | 150 | $50,000 |
| 9-RSW (Large) | 8 | 120,000 | 0.250 | 20,000 | 0.25 | 2,000,000 | 20,000 | 1 | 200 | $50,000 |
| 10-Fastening | 2 | 30,000 | 2.000 | 10,000 | 1.00 | 65,000 | 75,000 | 1 | 100 | $50,000 |
| F0 - RSW (Framer) | 8 | 120,000 | 1.000 | 10,000 | 1.00 | 250,000 | 900,000 | 2 | 250 | $600,000 |
| F1 - Laser (Framer) | 8 | 150,000 | 1.000 | 10,000 | 2.00 | 250,000 | 950,000 | 2 | 360 | $1,400,000 |
| 13-Hemming | 1 | 400,000 | 2.000 | 10,000 | 1.00 | 120,000 | 10,000 | 1 | 100 | $50,000 |
| 14-SPR (Rivet) | 2 | 120,000 | 2.000 | 10,000 | 1.00 | 50,000 | 50,000 | 1 | 100 | $50,000 |

**Table 7.2-10: General Assumptions for Assembly Cost**

| Parameters | Assumptions | |
|---|---|---|
| Available Operating Time | 3240 | hours / year |
| Paid Operating Time | 3456 | hours / year |
| Gross Line Rate | 62 | jph |
| Station Cycle Time for One Line | 58 | seconds |
| Actual Station Time | 58 | seconds |
| Number of Parallel Lines | 1 | |
| Part Loading Time | 5 | sec/part |
| Clamp/Unclamp Time | 6 | seconds |
| Transfer Time | 3 | seconds |
| Minimum Allowable Station Time | 30 | seconds |
| Transport System Cost per Station | 100000 | $/station |
| Assembly Unplanned Downtime | 1.6 | hrs/day |
| Assembly Maintenance Cost | 10% | |

## 8. Glossary of Terms and Initials

**Assembly:** a group of interdependent components joined together to perform a defined function (e.g., turbocharger assembly, high-pressure fuel pump assembly, high-pressure fuel injector assembly).

**Automatic Transmission (AT):** one type of motor vehicle transmission that can automatically change gear ratios as the vehicle moves, freeing the driver from having to shift gears manually.

**BAS (Belt Alternator Starter):** a system design to start/re-start an engine using a non-traditional internal combustion engine (ICE) starter motor. In a standard internal ICE the crankshaft drives an alternator, through a belt pulley arrangement, producing electrical power for the vehicle. In the BAS system, the alternator is replaced with a starter motor/generator assembly so that it can perform opposing duties. When the ICE is running, the starter motor/generator functions as a generator producing electricity for the vehicle. When the ICE is off, the starter motor/generator can function as a starter motor, turning the crankshaft to start the engine. In addition to starting the ICE, the starter motor can also provide vehicle launch assist and regenerative braking capabilities.

**BIW (Body in white)**: the stage in automotive design or manufacturing in which a car body's sheet metal components have been welded together — but before moving parts (doors, hoods, deck lids, fenders) the motor, chassis sub-assemblies, or trim (glass, seats, upholstery, electronics) have been added and before painting.

**Buy:** components or assemblies a manufacturer would purchase versus manufacture. All designated "buy" parts, within the analysis, only have a net component cost presented. These types of parts are typically considered commodity purchase parts having industry established pricing.

**CAD (Computer-aided Design):** use of computer systems to assist in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing.

**CAE (Computer-aided Engineering):** Computer software to assist in engineering and design tasks.

**CBOM (Comparison Bill of Materials):** a system bill of materials, identifying all the subsystems, assemblies, and components associated with the technology configurations under evaluation. The CBOM records all the high-level details of the technology configurations under study, identifies those items which have cost implication as a result of the new versus base technology differences, documents the study assumptions, and is the primary document for capturing input from the cross-functional team.

**CFA (Chemical Foaming Agent):** compound which facilitates the formation of foam or helps foam maintain its integrity by strengthening individual foam bubbles, acting as surfactants and reducing surface tension.

**Component:** the lowest level part within the cost analysis. An assembly is typically made up of several components acting together to perform a function (e.g., the turbine wheel in a turbocharger assembly). However, in some cases, a component can independently perform a function within a sub-subsystem or subsystem (e.g., exhaust manifold within the exhaust subsystem).

**Costing Databases:** the five core databases that contain all the cost rates for the analysis. (1) The **material database** lists all the materials used throughout the analysis along with the estimated price/pound for each. (2) The **labor database** captures various automotive, direct labor, manufacturing jobs (supplier and OEM), along with the associated mean hourly labor rates. (3) The **manufacturing overhead rate database** contains the cost/hour for the various pieces of manufacturing equipment assumed in the analysis. (4) A **mark-up database** assigns a percentage of mark-up for each of the four main mark-up categories (i.e., end-item scrap, SG&A, profit, and ED&T), based on the industry, supplier size, and complexity classification. (5) The **packaging database** contains packaging options and costs for each case.

**Dual Clutch Transmission (DCT):** is a differing type of semi-automatic or automated manual automotive transmission. It utilizes two separate clutches for odd and even gear sets. It can fundamentally be described as two separate manual transmissions (with their respective clutches) contained within one housing, and working as one unit. They are usually operated in a fully automatic mode, and many also have the ability to allow the driver to manually shift gears, albeit still carried out by the transmission's electro-hydraulics.

**ED&T (engineering, design, and testing):** initialism used in accounting to refer to engineering, design, and testing expenses.

**EPS:** Electric Power Steering.

**ESC:** Electronic Stability Control.

**FWD (Front-wheel Drive):** Not to be confused with four-wheel drive, which is commonly (and preferably) abbreviated as 4WD or AWD today.

**Gasoline Direct Inject (GDI):** variant of fuel injection employed in modern two-stroke and four-stroke gasoline engines. The gasoline is highly pressurized, and injected via a common rail fuel line directly into the combustion chamber of each cylinder, as opposed to conventional multi-point fuel injection that happens in the intake tract, or cylinder port.

**HEEDS® MDO:** Hierarchical Evolutionary Engineering Design System Multidisciplinary Design Optimization. It is a software package that interfaces with commercial CAE tools in order to automate and improve the search for better product and/or process designs. It generically interfaces with analysis codes through batch execution and different forms of scripting, but also includes direct interfaces to several commonly used CAE tools (e.g., Microsoft Excel, ABAQUS, Nastran).

**Hybrid Electric Vehicle (HEV):** type of hybrid vehicle and electric vehicle which combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system.

**Internal Combustion Engine (ICE):** an engine in which the combustion of a fuel occurs with an oxidizer in a combustion chamber.

**Indirect Cost Multipliers (ICM):** developed by the EPA to address the OEM indirect costs associated with manufacturing new components and assemblies. The indirect costs, costs associated with OEM research and development, corporate operations, dealership support, sales and marketing material, legal, and OEM owned tooling, are calculated by applying an ICM factor to the direct manufacturing cost.

**Indirect Labor (IND):** manufacturing labor indirectly associated with making a physical component or assembly.

**Intellectual property** (**IP**): distinct types of creations of the mind for which a set of exclusive rights are recognized under the corresponding fields of law.

**Lean Design® (a module within the *Design Profit®* software*):*** used to create detailed process flow charts/process maps. Lean Design uses a series of standardized symbols, with each base symbol representing a group of similar manufacturing procedures (e.g., fastening, material modifications, inspection). For each group, a Lean Design library/database exists containing standardized operations along with the associated manufacturing information and specifications for each operation. The information and specifications are used to generate a net operation cycle time. Each operation on a process flow chart is represented by a base symbol, operation description, and operation time, all linked to a Lean Design library/database.

**Maintenance Repair (MRO):** all actions which have the objective of retaining or restoring an item in or to a state in which it can perform its required function. The actions include the combination of all technical and corresponding administrative, managerial, and supervision actions

**Make:** components or assemblies a manufacturer would produce internally versus purchase. All parts designated as a “make” part, within the analysis, are costed in full detail.

**MAQS (Manufacturing Assumption and Quote Summary) worksheet**: standardized template used in the analysis to calculate the mass production manufacturing cost, including supplier mark-up, for each system, subsystem, and assembly quoted in the analysis. Every component and assembly costed in the analysis will have a MAQS worksheet. The worksheet is based on a standard OEM (original equipment manufacturer) quote sheet modified for improved costing transparency and flexibility in sensitivity studies. The main feeder documents to the MAQS worksheets are **process maps** and the **costing databases**.

**MCR (Material Cost Reduction):** process employed to identify and capture potential design and/or manufacturing optimization ideas with the hardware under evaluation. These savings could potentially reduce or increase the differential costs between the new and base technology configurations, depending on whether an MCR idea is for the new or the base technology.

**MDO (Multidisciplinary Design Optimization):** a field of engineering that uses optimization methods to solve design problems incorporating a number of disciplines.

**Metal Injection Molding** (**MIM**): metalworking process where finely-powdered metal is mixed with a measured amount of binder material to comprise a 'feedstock' capable of being handled by plastic processing equipment through a process known as injection mold forming.

**MMC (Metal Matrix Composite):** composite material with at least two constituent parts, one being a metal. The other material may be a different metal or another material, such as a ceramic or organic compound.

**MSRP:** Manufacturing Suggested Retail Price.

**Naturally Aspirated (NA):** common type of reciprocating piston internal combustion that depends solely on atmospheric pressure to counter the partial vacuum in the induction tract to draw in combustion air.

**Net Component/Assembly Cost Impact to OEM:** the net manufacturing cost impact per unit to the OEM for a defined component, assembly, subsystem, or system. For components produced by the supplier base, the net manufacturing cost impact to the OEM includes total manufacturing costs (material, labor, and manufacturing overhead), mark-up (end-item scrap costs, selling, general and administrative costs, profit, and engineering design and testing costs) and packaging costs. For OEM internally manufactured components, the net manufacturing cost impact to the OEM includes total manufacturing costs and packaging costs; mark-up costs are addressed through the application of an indirect cost multiplier.

**NCAC:** National Crash Analysis Center.

**NHTSA:** National Highway Transportation Safety Administration.

**NIDMC:** Net Incremental Direct Manufacturing Cost.

**NTA (New Technology Advances):** a process employed to identify and capture alternative advance technology ideas which could be substituted for some of the existing hardware under evaluation. These advanced technologies, through improved function and performance, and/or cost reductions, could help increase the overall value of the technology configuration.

**NVH (Noise Vibration Harshness):** the study and modification of the noise and vibration characteristics of vehicles.

**OEM:** Original Equipment Manufacturer manufactures products or components that are purchased by another company and retailed under that purchasing company's brand name. OEM refers to the company that originally manufactured the product. When referring to automotive parts, OEM designates a replacement part made by the manufacturer of the original part.

**Port Fuel Injected (PFI):** method for admitting fuel into an internal combustion engine by fuel injector sprays into the port of the intake manifold.

**Powertrain Package Proforma:** a summary worksheet comparing the key physical and performance attributes of the technology under study with those of the corresponding base configuration.

**Power-Split HEV:** In a power-split hybrid electric drive train there are two motors: an electric motor and an internal combustion engine. The power from these two motors can be shared to drive the wheels via a power splitter, which is a simple planetary gear set.

**Process Maps**: detailed process flow charts used to capture the operations and processes and associated key manufacturing variables involved in manufacturing products at any level (e.g., vehicle, system, subsystem, assembly, and component).

**PTWA (Plasma Transferred Wire Arc):** a thermal spraying process that deposits a coating on the internal surface of a cylindrical surface, or external surface of any geometry. It is predominantly known for its use in coating the cylinder bores of an engine, enabling the use of aluminum engine blocks without the need for heavy cast iron sleeves.

**P-VCSM (Powertrain–Vehicle Class Summary Matrix):** records the technologies being evaluated, the applicable vehicle classes for each technology, and key parameters for vehicles or vehicle systems that have been selected to represent the new technology and baseline configurations in each vehicle class to be costed.

**Quote:** the analytical process of establishing a cost for a component or assembly.

**Risk:** state of uncertain probabilities that exist in which the possibilities of outcome are not entirely certain or are measured by percentiles in terms of success, failure, loss, gain, etc.

**RPE:** Retail Price Equivalent.

**SG&A (Selling General and Administrative):** is an acronym used in accounting to refer to Selling, General and Administrative Expenses, which is a major non-production costs presented in an Income statement.

**SMS (Secondary Mass Savings):** mass decompounding.

**Sub-subsystem:** a group of interdependent assemblies and/or components, required to create a functioning sub-subsystem. For example, the air induction subsystem contains several sub-subsystems including turbocharging, heat exchangers, pipes, hoses, and ducting.

**Subsystem:** a group of interdependent sub-subsystems, assemblies and/or components, required to create a functioning subsystem. For example, the engine system contains several subsystems including crank drive subsystem, cylinder block subsystem, cylinder head subsystem, fuel induction subsystem, and air induction subsystem.

**Subsystem CMAT (Cost Model Analysis Templates):** the document used to display and roll up all the sub-subsystem, assembly, and component incremental costs associated with a subsystem (e.g., fuel induction, air induction, exhaust), as defined by the Comparison Bill of Material (CBOM).

**Surrogate part:** a part similar in fit, form, and function as another part that is required for the cost analysis. Surrogate parts are sometimes used in the cost analysis when actual parts are unavailable. The surrogate part's cost is considered equivalent to the actual part's cost.

**System:** a group of interdependent subsystems, sub-subsystems, assemblies, and/or components working together to create a vehicle primary function (e.g., engine system, transmission system, brake system, fuel system, suspension system).

**System CMAT (Cost Model Analysis Template):** the document used to display and roll up all the subsystem incremental costs associated with a system (e.g., engine, transmission, steering) as defined by the CBOMs.